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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
22 March 2007 (22.03.2007)

PCT

(10) **International Publication Number**
WO 2007/031991 A2

(51) **International Patent Classification:**
G02B 27/01 (2006.01) ***G02B 6/00*** (2006.01) ***G02B 5/32*** (2006.01)

(21) **International Application Number:** PCT/IL2006/001050

(22) **International Filing Date:** 7 September 2006 (07.09.2006)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**

60/716,533	14 September 2005 (14.09.2005)	US
60/732,661	3 November 2005 (03.11.2005)	US
60/801,410	19 May 2006 (19.05.2006)	US
11/505,866	18 August 2006 (18.08.2006)	US

(63) **Related by continuation (CON) or continuation-in-part (CIP) to earlier application:**
US 11/505,866 (CIP)
Filed on 18 August 2006 (18.08.2006)

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US (patent), UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** DIFFRACTIVE OPTICAL DEVICE AND SYSTEM

(57) **Abstract:** An optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view is provided. The device comprises a light-transmissive substrate, an input optical element and an output optical element. The input element diffracts the light to propagate within the light-transmissive substrate via total internal reflection, and the output element diffracts the light out of the substrate. The output element is characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within the field-of-view is directed to a two-dimensional region being at a predetermined distance from the substrate.

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DIFFRACTIVE OPTICAL DEVICE AND SYSTEM

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to optics and, more particularly, to an optical system and device diffracting light into one or more two-dimensional regions.

Miniaturization of electronic devices has always been a continuing objective in the field of electronics. Electronic devices are often equipped with some form of a display, which is visible to a user. As these devices reduce in size, there is an increase need for manufacturing compact displays, which are compatible with small size electronic devices. Besides having small dimensions, such displays should not sacrifice image quality, and be available at low cost. By definition the above characteristics are conflicting and many attempts have been made to provide some balanced solution.

An electronic display may provide a real image, the size of which is determined by the physical size of the display device, or a virtual image, the size of which may extend the dimensions of the display device.

A real image is defined as an image, projected on or displayed by a viewing surface positioned at the location of the image, and observed by an unaided human eye (to the extent that the viewer does not require corrective glasses). Examples of real image displays include a cathode ray tube (CRT), a liquid crystal display (LCD), an organic light emitting diode array (OLED), or any screen-projected displays. A real image could be viewed normally from a distance of about at least 25 cm, the minimal distance at which the human eye can utilize focus onto an object. Unless a person is long-sighted, he may not be able to view a sharp image at a closer distance.

Typically, desktop computer systems and workplace computing equipment utilize CRT display screens to display images for a user. The CRT displays are heavy, bulky and not easily miniaturized. For a laptop, a notebook, or a palm computer, flat-panel display is typically used. The flat-panel display may use LCD technology implemented as passive matrix or active matrix panel. The passive matrix LCD panel consists of a grid of horizontal and vertical wires. Each intersection of the grid constitutes a single pixel, and controls an LCD element. The LCD element either allows light through or blocks the light. The active matrix panel uses a transistor to control each pixel, and is more expensive.

An OLED flat panel display is an array of light emitting diodes, made of organic polymeric materials. Existing OLED flat panel displays are based on both passive and active configurations. Unlike the LCD display, which controls light transmission or reflection, an OLED display emits light, the intensity of which is controlled by the electrical bias applied thereto. Flat-panels are also used for miniature image display systems because of their compactness and energy efficiency compared to the CRT displays. Small size real image displays have a relatively small surface area on which to present a real image, thus have limited capability for providing sufficient information to the user. In other words, because of the limited resolution of the human eye, the amount of details resolved from a small size real image might be insufficient.

By contrast to a real image, a virtual image is defined as an image, which is not projected onto or emitted from a viewing surface, and no light ray connects the image and an observer. A virtual image can only be seen through an optic element, for example a typical virtual image can be obtained from an object placed in front of a converging lens, between the lens and its focal point. Light rays, which are reflected from an individual point on the object, diverge when passing through the lens, thus no two rays share two endpoints. An observer, viewing from the other side of the lens would perceive an image, which is located behind the object, hence enlarged. A virtual image of an object, positioned at the focal plane of a lens, is said to be projected to infinity. A virtual image display system, which includes a miniature display panel and a lens, can enable viewing of a small size, but high content display, from a distance much smaller than 25 cm. Such a display system can provide a viewing capability which is equivalent to a high content, large size real image display system, viewed from much larger distance.

Conventional virtual image displays are known to have many shortcomings. For example, such displays have suffered from being too heavy for comfortable use, as well as too large so as to be obtrusive, distracting and even disorienting. These defects stem from, *inter alia*, the incorporation of relatively large optics systems within the mounting structures, as well as physical designs which fail to adequately take into account important factors as size, shape, weight, *etc.*

Recently, holographic optical elements have been used in portable virtual image displays. Holographic optical elements serve as an imaging lens and a

combiner where a two-dimensional, quasi-monochromatic display is imaged to infinity and reflected into the eye of an observer. A common problem to all types of holographic optical elements is their relatively high chromatic dispersion. This is a major drawback in applications where the light source is not purely monochromatic. Another drawback of some of these displays is the lack of coherence between the geometry of the image and the geometry of the holographic optical element, which causes aberrations in the image array that decrease the image quality.

New designs, which typically deal with a single holographic optical element, compensate for the geometric and chromatic aberrations by using non-spherical waves rather than simple spherical waves for recording; however, they do not overcome the chromatic dispersion problem. Moreover, with these designs, the overall optical systems are usually very complicated and difficult to manufacture. Furthermore, the field-of-view resulting from these designs is usually very small.

U.S. Patent No. 4,711,512 to Upatnieks describes a diffractive planar optics head-up display configured to transmit collimated light wavefronts of an image, as well as to allow light rays coming through the aircraft windscreen to pass and be viewed by the pilot. The light wavefronts enter an elongated optical element located within the aircraft cockpit through a first diffractive element, are diffracted into total internal reflection within the optical element, and are diffracted out of the optical element by means of a second diffractive element into the direction of the pilot's eye while retaining the collimation. Upatnieks, however, does not teach how to transmit a wide field-of-view through the display, or how to transmit a broad spectrum of wavelengths (for providing color images). A major limitation of the head-up display of Upatnieks is the use of thick volume holograms which, albeit their relatively high diffraction efficiency, are known to have narrow angular and chromatic response.

U.S. Patent Nos. 5,966,223 and 5,682,255 to Friesem *et al.* describes a holographic optical device similar to that of Upatnieks, with the additional aspect that the first diffractive optical element acts further as the collimating element that collimates the waves emitted by each data point in a display source and corrects for field aberrations over the entire field-of-view. The field-of-view discussed is ±6°, and there is a further discussion of low chromatic sensitivity over wavelength shift of $\Delta\lambda_c$ of ±2 nm around a center wavelength λ_c of 632.8 nm. However, the diffractive collimating element of Friesem *et al.* is known to narrow spectral response, and the

low chromatic sensitivity at spectral range of ±2 nm becomes an unacceptable sensitivity at ±20 nm or ±70 nm.

U.S. Patent No. 6,757,105 to Niv *et al.*, the contents of which are hereby incorporated by reference, provides a diffractive optical element for optimizing a field-of-view for a multicolor spectrum. The optical element includes a light-transmissive substrate and a linear grating formed therein. Niv *et al.* teach how to select the pitch of the linear grating and the refraction index of the light-transmissive substrate so as to trap a light beam having a predetermined spectrum and characterized by a predetermined field of view to propagate within the light-transmissive substrate via total internal reflection. Niv *et al.* also disclose an optical device incorporating the aforementioned diffractive optical element for transmitting light in general and images in particular into the eye of the user.

The above virtual image devices, however, provide a single optical channel, hence allowing the scene of interest to be viewed by one eye. It is recognized that the ability of any virtual image devices to transmit an image without distortions inherently depends on whether or not light rays emanating from all points of the image are successfully transmitted to the eye of the user in their original color. Due to the single optical channel employed by presently known devices, the filed-of-view which can be achieved without distortions or loss of information is rather limited.

A binocular device which employs several diffractive optical elements is disclosed in U.S. Patent Application Nos. 10/896,865 and 11/017,920, and in International Patent Application, Publication No. WO 2006/008734, the contents of which are hereby incorporated by reference. An optical relay is formed of a light transmissive substrate, an input diffractive optical element and two output diffractive optical elements. Collimated light is diffracted into the optical relay by the input diffractive optical element, propagates in the substrate via total internal reflection and coupled out of the optical relay by two output diffractive optical elements. The input and output diffractive optical elements preserve relative angles of the light rays to allow transmission of images with minimal or no distortions. The output elements are spaced apart such that light diffracted by one element is directed to one eye of the viewer and light diffracted by the other element is directed to the other eye of the viewer. The binocular design of these references significantly improves the field-of-view.

In a binocular system of the type descried above, the distance between the output optical elements should, in principle, match the interpupillary distance of the individual using the system. On the other hand, the interpupillary distance may vary by more than 50 % from one individual to another. Such binocular systems therefore provide different viewing conditions to individuals with different interpupillary distances. In other words, a binocular system which provides optimal viewing conditions for one individual may provide less than optimal viewing conditions for another individual, particularly when the interpupillary distances of the two individuals significantly differ.

There is thus a widely recognized need for, and it would be highly advantageous to have an optical device and system devoid of the above limitations.

SUMMARY OF THE INVENTION

According to one aspect of the present invention there is provided an optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view. The device comprises a light-transmissive substrate engaging a plane spanned by a longitudinal direction and a transverse direction. The optical relay device further comprises an input optical element, designed and constructed for redirecting the light such that the light propagates within the light-transmissive substrate via total internal reflection; and an output optical element, laterally displaced from the input optical element, and being designed and constructed for redirecting the light out of the light-transmissive substrate. The output optical element of the device is characterized by planar dimensions defined by a length along the longitudinal direction and a width along the transverse direction, where the length and the width are selected such that at least a portion of one or more outermost light ray within the field-of-view is directed to a two-dimensional region being at a predetermined distance from the light transmissive substrate.

According another aspect of the present invention there is provided an optical relay device. The device comprises a light-transmissive substrate engaging a plane as described above; an input optical element designed and constructed for redirecting the light such that the light propagates within the light-transmissive substrate via total internal reflection; and one or more output optical element, laterally displaced from the input optical element, and being designed and constructed for redirecting the light out

of the light-transmissive substrate. Each of the input optical element and the output optical element(s) of the device being characterized by planar dimensions defined by a length along the longitudinal direction and a width along the transverse direction, where a width of the output optical element is smaller than a width of the input optical element.

According to another aspect of the present invention there is provided an optical relay device. The device comprises, a light-transmissive substrate engaging a plane as described above, an input optical element designed and constructed for redirecting the light such that the light propagates within the light-transmissive substrate via total internal reflection; a first output optical element, laterally displaced from the input optical element, and being designed and constructed for redirecting light corresponding to a first partial field-of-view out of the light-transmissive substrate; and a second output optical element, laterally displaced from the input optical element and the first output optical element, and being designed and constructed for redirecting light corresponding to a second partial field-of-view out of the light-transmissive substrate. Each of the first and second output optical elements being characterized by planar dimensions defined by a length along the longitudinal direction and a width along the transverse direction, wherein a length and a width of the first output optical element are selected such that at least a portion of one or more outermost light ray within the first partial field-of-view is directed to a first two-dimensional region, and a length and a width of the second output optical element are selected such that at least a portion of one or more outermost light ray within the second partial field-of-view is directed to a second two-dimensional region, the first and the second two-dimensional regions being at a predetermined distance from the light transmissive substrate.

According to still further features in the described preferred embodiments the planar dimensions are selected such that the portions of the outermost light rays are respectively directed to the first and the second two-dimensional regions, for any lateral separation between the centers two-dimensional regions which is larger than Y1 millimeters and smaller than Y2 millimeters, where Y1 can be any number larger or equal 40 and Y2 can be any number smaller or equal 80.

According to still further features in the described preferred embodiments Y1 equals about 50 and Y2 equals about 65; alternatively, Y1 equals about 53 and Y2

equals about 73; alternatively, Y2 is larger than Y1 by about 10 millimeters and Y1 can be any number from about 53 to about 63, including, without limitation, 53, 58 or 63.

According to still further features in the described preferred embodiments the input and/or output optical element is a diffractive optical element.

According to still another aspect of the present invention there is provided an optical relay device for transmitting an image by diffraction to a first eye and a second eye characterized by an interpupillary distance, the device comprises a light transmissive substrate and a plurality of diffractive optical elements located at fixed locations on the light transmissive substrate, the diffractive optical relay device being characterized by a field-of-view of at least 16 degrees, and being capable of providing the image for any interpupillary distance from Y1 millimeters to Y2 millimeters, as described above.

According to yet another aspect of the present invention there is provided a system for providing an image to a user. The system comprises the optical relay device and an image generating system for providing the diffractive optical relay device with collimated light constituting the image.

According to further features in preferred embodiments of the invention described below, the width of the output optical element(s) is smaller than the width of the input optical element.

According to still further features in the described preferred embodiments the plurality of diffractive optical elements comprises an input diffractive optical element, a first output diffractive optical element and a second output diffractive optical element, the input diffractive optical element being designed and constructed for diffracting light constituting the image to propagate within the light-transmissive substrate via total internal reflection, and the output diffractive optical elements being designed and constructed for diffracting at least a portion of the light out of the light transmissive substrate.

According to still further features in the described preferred embodiments the first output diffractive optical element is designed and constructed for diffracting light corresponding to a first partial field-of-view of the image out of the light-transmissive substrate, and the second output diffractive optical element is designed and constructed for diffracting light corresponding to a second partial field-of-view of the

image out of the light-transmissive substrate, such that the combination of the first and the second partial field-of-views substantially reconstructs the field-of-view.

According to still further features in the described preferred embodiments the first and the second diffractive optical elements are characterized by planar dimensions selected such that at least a portion of one or more outermost light ray within the first partial field-of-view is directed to a first two-dimensional region containing the first eye, and at least a portion of one or more outermost light ray within the second partial field-of-view is directed to a second two-dimensional region containing the second eye, the first and the second two-dimensional regions being at a predetermined distance from the light transmissive substrate.

According to still further features in the described preferred embodiments the predetermined distance is from about Z1 millimeters to Z2 millimeters, where Z1 is preferably about 15 and Z2 can be any number from about 20 to about to about 35, including, without limitation, about 20, about 25, about 30 and about 35.

According to still further features in the described preferred embodiments a width of the two-dimensional region is from about 4 millimeters to about 9 millimeters. According to still further features in the described preferred embodiments a length of the two-dimensional region is from about 5 millimeters to about 13 millimeters.

According to still further features in the described preferred embodiments a length of the input optical element equals from about X to about 3X where X is a minimal unit hop-length characterizing propagation of an outermost light ray within the light transmissive substrate via total internal reflection.

According to still further features in the described preferred embodiments wherein the light is characterized by a spectrum inclusively defined between a shortest wavelength and a longest wavelength. According to still further features in the described preferred embodiments the length of the input optical element equals from about X to about 3X where X is a unit hop-length characterizing propagation of a light ray having the shortest wavelength within the light transmissive substrate via total internal reflection.

According to still further features in the described preferred embodiments one or more of the diffractive optical elements comprises a grating described by non-uniform diffraction efficiency function.

According to still further features in the described preferred embodiments the grating has a periodic linear structure in one or more direction, the periodic linear structure being characterized by non-uniform duty cycle.

According to still further features in the described preferred embodiments the grating has a periodic linear structure in one or more direction, the periodic linear structure being characterized by non-uniform modulation depth.

According to still further features in the described preferred embodiments the grating has a periodic linear structure in one or more direction, the periodic linear structure being characterized by non-uniform duty cycle and non-uniform modulation depth.

According to still further features in the described preferred embodiments the non-uniform diffraction efficiency function is monotonic across the one or more direction.

According to still further features in the described preferred embodiments the non-uniform diffraction efficiency function is selected such that when a light ray impinges on the grating a plurality of times, a predetermined and substantially constant fraction of the energy of the light is diffracted at each impingement.

According to still further features in the described preferred embodiments the grating is formed in the light transmissive substrate.

According to still further features in the described preferred embodiments the grating is attached to the light transmissive substrate.

The present invention successfully addresses the shortcomings of the presently known configurations by providing an optical relay device and a system incorporating the optical relay device.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

In the drawings:

FIG. 1 is a schematic illustration of light diffraction by a linear diffraction grating operating in transmission mode;

FIGs. 2a-c are schematic illustrations of cross sectional views of an optical relay device according to various exemplary embodiments of the invention;

FIG. 2d is a schematic illustration of a rechtangular field-of-view of the optical relay device, according to various exemplary embodiments of the invention;

FIGs. 2e-f are schematic illustrations of field-of-view angles of the optical relay device, according to various exemplary embodiments of the invention;

FIGs. 3a-b are schematic illustrations of a perspective view (Figure 3a) and a side view (Figure 3b) of the optical relay device, in a preferred embodiment in which the device comprises one input optical element and two output optical elements, according to various exemplary embodiments of the present invention;

FIGs. 4a-b are fragmentary views schematically illustrating wavefront propagation within the optical relay device, according to preferred embodiments of the present invention;

FIGs. 5a-b are schematic illustrations of a fragmentary top view (Figure 5a) and a fragmentary side view (Figure 5b) of the relay device in a preferred embodiment in which one or more of the diffractive optical elements of the device comprises a grating;

FIG. 6 is a schematic illustration of a grating having a non-uniform duty cycle, according to various exemplary embodiments of the present invention;

FIG. 7 is a schematic illustration of a grating having a non-uniform modulation depth, according to various exemplary embodiments of the present invention;

FIG. 8 is a schematic illustration of a grating having a non-uniform duty cycle and a non-uniform modulation depth, according to various exemplary embodiments of the present invention;

FIG. 9 is a schematic illustration of binocular system, according to various exemplary embodiments of the present invention;

FIGs. 10a-c are schematic illustrations of a wearable device, according to various exemplary embodiments of the present invention;

FIGs. 11a-d is a graph showing numerical calculations of the diffraction efficiency of a grating as a function of the duty cycle, for impinging angles of 50° (Figures 11a-b) and 55° (Figures 11c-d), and modulation depths of 150 nm (Figures 11a and 11c) and 300 nm (Figures 11b and 11d); and

FIGs. 12a-b is a graph showing numerical calculations of the diffraction efficiency of a grating as a function of the modulation depth, for duty cycle of 0.5 and impinging angles of 50° (Figure 12a) and 55° (Figure 12b).

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present embodiments comprise a device and system which can be used for transmitting light. Specifically, but not exclusively, the present embodiments can be used for providing virtual images. The present embodiments can be used in many applications in which virtual images are viewed, including, without limitation, eyeglasses, binoculars, head mounted displays, head-up displays, cellular telephones, personal digital assistants, aircraft cockpits and the like.

The principles and operation of a device and system according to the present invention may be better understood with reference to the drawings and accompanying descriptions.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways. Also, it is to be

understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

When a ray of light moving within a light-transmissive substrate and striking one of its internal surfaces at an angle ϕ_1 as measured from a normal to the surface, it can be either reflected from the surface or refracted out of the surface into the open air in contact with the substrate. The condition according to which the light is reflected or refracted is determined by Snell's law, which is mathematically realized through the following equation:

$$n_A \sin \phi_2 = n_S \sin \phi_1, \qquad \text{(EQ. 1)}$$

where n_S is the index of refraction of the light-transmissive substrate, n_A is the index of refraction of the medium outside the light transmissive substrate ($n_S > n_A$), and ϕ_2 is the angle in which the ray is refracted out, in case of refraction. Similarly to ϕ_1, ϕ_2 is measured from a normal to the surface. A typical medium outside the light transmissive substrate is air having an index of refraction of about unity.

As used herein, the term "about" refers to ±10 %.

As a general rule, the index of refraction of any substrate depends on the specific wavelength λ of the light which strikes its surface. Given the impact angle, ϕ_1, and the refraction indices, n_S and n_A, Equation 1 has a solution for ϕ_2 only for ϕ_1 which is smaller than arcsine of n_A/n_S often called the critical angle and denoted α_c. Hence, for sufficiently large ϕ_1 (above the critical angle), no refraction angle ϕ_2 satisfies Equation 1 and light energy is trapped within the light-transmissive substrate. In other words, the light is reflected from the internal surface as if it had stroked a mirror. Under these conditions, total internal reflection is said to take place. Since different wavelengths of light (*i.e.*, light of different colors) correspond to different indices of refraction, the condition for total internal reflection depends not only on the angle at which the light strikes the substrate, but also on the wavelength of the light. In other words, an angle which satisfies the total internal reflection condition for one wavelength may not satisfy this condition for a different wavelength.

When a sufficiently small object or sufficiently small opening in an object is placed in the optical path of light, the light experiences a phenomenon called diffraction in which light rays change direction as they pass around the edge of the object or at the opening thereof. The amount of direction change depends on the ratio

between the wavelength of the light and the size of the object/opening. In planar optics there is a variety of optical elements which are designed to provide an appropriate condition for diffraction. Such optical elements are typically manufactured as diffraction gratings which are located on a surface of a light-transmissive substrate. Diffraction gratings can operate in transmission mode, in which case the light experiences diffraction by passing through the gratings, or in reflective mode in which case the light experiences diffraction while being reflected off the gratings

Figure 1 schematically illustrates diffraction of light by a linear diffraction grating operating in transmission mode. One of ordinary skills in the art, provided with the details described herein would know how to adjust the description for the case of reflection mode.

A wavefront **1** of the light propagates along a vector $\underline{i}$ and impinges upon a grating **2** engaging the x-y plane. The normal to the grating is therefore along the z direction and the angle of incidence of the light ϕ_i is conveniently measured between the vector $\underline{i}$ and the z axis. In the description below, ϕ_i is decomposed into two angles, ϕ_{ix} and ϕ_{iy}, where ϕ_{ix} is the incidence angle in the z-x plane, and ϕ_{iy} is the incidence angle in the z-y plane. For clarity of presentation, only ϕ_{iy} is illustrated in Figure 1.

The grating has a periodic linear structure along a vector g, forming an angle θ_R with the y axis. The period of the grating (also known as the grating pitch) is denoted by D. The grating is formed on a light transmissive substrate having an index of refraction denoted by n_S.

Following diffraction by grating **2**, wavefront **1** changes its direction of propagation. The principal diffraction direction which corresponds to the first order of diffraction is denoted by $\underline{d}$ and illustrated as a dashed line in Figure 1. Similarly to the angle of incidence, the angle of diffraction ϕ_d, is measured between the vector $\underline{d}$ and the z axis, and is decomposed into two angles, ϕ_{dx} and ϕ_{dy}, where ϕ_{dx} is the diffraction angle in the z-x plane, and ϕ_{dy} is the diffraction angle in the z-y plane.

The relation between the grating vector g, the diffraction vector $\underline{d}$ and the incident vector $\underline{i}$ can therefore be expressed in terms of five angles (θ_R, ϕ_{ix}, ϕ_{iy}, ϕ_{dx} and ϕ_{dy}) and it generally depends on the wavelength λ of the light and the grating period D through the following pair of equations:

$$\sin(\phi_{ix}) - n_S \sin(\phi_{dx}) = (\lambda/D)\sin(\theta_R) \qquad \text{(EQ. 2)}$$

$$\sin(\phi_{iy}) + n_S \sin(\phi_{dy}) = (\lambda/D)\cos(\theta_R). \qquad \text{(EQ. 3)}$$

Without the loss of generality, the Cartesian coordinate system can be selected such that the vector $\underline{i}$ lies in the y-z plane, hence $\sin(\phi_{ix}) = 0$. In the special case in which the vector g lies along the y axis, $\theta_R = 0°$ or $180°$, and Equations 2-3 reduce to the following one-dimensional grating equation:

$$\sin \phi_{iy} + n_S \sin \phi_{dy} = \pm\lambda/d. \qquad \text{(EQ. 4)}$$

According the known conventions, the sign of ϕ_{ix}, ϕ_{iy}, ϕ_{dx} and ϕ_{dy} is positive, if the angles are measured clockwise from the normal to the grating, and negative otherwise. The dual sign on the RHS of the one-dimensional grating equation relates to two possible orders of diffraction, +1 and −1, corresponding to diffractions in opposite directions, say, "diffraction to the right" and "diffraction to the left," respectively.

A light ray, entering a substrate through a grating, impinge on the internal surface of the substrate opposite to the grating at an angle which depends on the two diffraction components $\sin(\phi_{dx})$ and $\sin(\phi_{dy})$ according to the following equation:

$$\phi_d = \sin^{-1}\{[\sin^2(\phi_{dx}) + \sin^2(\phi_{dy})]^{1/2}\} \qquad \text{(EQ. 5)}$$

When ϕ_d is larger than the critical angle α_c, the wavefront undergoes total internal reflection and begin to propagate within the substrate.

Reference is now made to Figures 2a-c which are schematic illustrations of cross sectional views of an optical relay device **10**, according to various exemplary embodiments of the present invention. Figures 2a, 2b and 2c illustrate cross sectional views of device **10** in the x-y plane, y-z plane and the x-z plane, respectively. Device **10** comprises a light-transmissive substrate **14**, an input optical element **13** and an output optical element **15**. The system of coordinates in Figures 2a-c is selected such that substrate **14** is orthogonal to the z axis, and optical elements **13** and **15** are laterally displaced along the y axis. Generally, the z axis is referred to as the "normal axis", the y axis is referred to as the "longitudinal axis" and the x axis is referred to as the "transverse axis" of device **10**. Thus, substrate **14** engages a plane spanned by the longitudinal direction (the y direction in the present coordinate system) and the transverse direction (the x direction in the present coordinate system).

Element **13** redirects the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**. Element **15** serves for redirecting at least a few of the propagating light rays out of substrate **14**. Each of elements **13** and **15** can be a refractive element, a reflective element or a diffractive element.

In embodiments in which a refractive element is employed, element **13** and/or element **15** can comprise a plurality of linearly stretched mini- or micro-prisms, and the redirection of light is generally by the refraction phenomenon described by Snell's law. Thus, for example, when both elements **13** and **15** are refractive elements, element **13** refracts the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** refracts at least a few of the propagating light rays out of substrate **14**. Refractive elements in the form of mini- or micro-prisms are known in the art and are found, *e.g.*, in U.S. Patent Nos. 5,969,869, 6,941,069 and 6,687,010, the contents of which are hereby incorporated by reference.

In embodiments in which a reflective element is employed, element **13** and/or element **15** can comprises a plurality of dielectric mirrors, and the redirection of light is generally by the reflection phenomenon, described by the basic law of reflection. Thus, for example, when both elements **13** and **15** are reflective elements, element **13** reflects the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** reflects at least a few of the propagating light rays out of substrate **14**. Reflective elements in the form of dielectric mirrors are known in the art and are found, *e.g.*, in U.S. Patent Nos. 6,330,388 and 6,766,082, the contents of which are hereby incorporated by reference.

Element **13** and/or element **15** can also combine reflection with refraction. For example, element **13** and/or element **15** can comprise a plurality of partially reflecting surfaces located in substrate **14**. In this embodiment, the partially reflecting surfaces are preferably parallel to each other. Optical elements of this type are known in the art and found, *e.g.*, in U.S. Patent No. 6,829,095, the contents of which are hereby incorporated by reference.

In embodiments in which diffractive element is employed, element **13** and/or **15** can comprise a grating and the redirection of light is generally by the diffraction phenomenon. Thus, for example, when both elements **13** and **15** are diffractive

elements, element **13** diffracts the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** diffracts at least a few of the propagating light rays out of substrate **14**.

The term "diffracting" as used herein, refers to a change in the propagation direction of a wavefront, in either a transmission mode or a reflection mode. In a transmission mode, "diffracting" refers to change in the propagation direction of a wavefront while passing through the diffractive element; in a reflection mode, "diffracting" refers to change in the propagation direction of a wavefront while reflecting off the diffractive element in an angle different from the basic reflection angle (which is identical to the angle of incidence). In the exemplified illustration of Figure 2b, elements **13** and **15** are transmissive elements, *i.e.*, they operates in transmission mode.

Input element **13** is designed and constructed such that the angle of light rays redirected thereby is above the critical angle, and the light propagates in the substrate via total internal reflection. The propagated light, after a few reflections within substrate **14**, reaches output element **15** which redirects the light out of substrate **14**.

Element **13** and/or element **15** is optionally and preferably a linear diffraction grating, operating according to the principles described above. When both elements **13** and **15** are linear ratings, their periodic linear structures are preferably substantially parallel. Elements **13** and **15** can be formed on or attached to any of the surfaces **23** and **24** of substrate **14**. Substrate **14** can be made of any light transmissive material, preferably, but not obligatorily, a martial having a sufficiently low birefringence. Element **15** is laterally displaced from element **13**. A preferred lateral separation between the elements is from a few millimeters to a few centimeters.

Device **10** is preferably designed to transmit light striking substrate **14** at any striking angle within a predetermined range of angles, which predetermined range of angles is referred to of the field-of-view of the device.

The input optical element is designed to trap all light rays in the field-of-view within the substrate. A field-of-view can be expressed either inclusively, in which case its value corresponds to the difference between the minimal and maximal incident angles, or explicitly in which case the field-of-view has a form of a mathematical range or set. Thus, for example, a field-of-view, Ω, spanning from a minimal incident angle, α, to a maximal incident angle, β, is expressed inclusively as $\Omega = \beta - \alpha$, and

exclusively as $\Omega = [\alpha, \beta]$. The minimal and maximal incident angles are also referred to as rightmost and leftmost incident angles or counterclockwise and clockwise field-of-view angles, in any combination. The inclusive and exclusive representations of the field-of-view are used herein interchangeably.

The field-of-view of device **10** is illustrated in Figures 2b-f by two of its outermost light rays, generally shown at **17** and **18**.

Figure 2b and 2c illustrate the projections of rays **17** and **18** on two planes which are parallel to the normal axis of device **10**. Specifically, Figure 2b illustrates the projections of rays **17** and **18** on a plane containing the longitudinal axis of device **10** (the *y-z* plane in the present coordinate system) and Figure 2c illustrates the projections of rays **17** and **18** on a plane containing the transverse axis of device **10** (the *x-z* plane in the present coordinate system).

Below, the terms "longitudinal field-of-view" and "transverse field-of-view" will be used to describe the ranges angles within the field-of-view as projected on the *y-z* and *x-z* planes respectively.

Thus, Figure 2b schematically illustrates the longitudinal field-of-view and Figure 2c schematically illustrates the transverse field-of-view of device **10**. In the longitudinal field-of-view illustrated in Figure 2b, the projection of ray **18** is the rightmost ray projection which forms with the normal axis an angle denoted θ_y^-, and the projection of ray **17** is the leftmost ray projection which forms with the normal axis an angle denoted θ_y^+. In the transverse field-of-view illustrated in Figure 2c, the projection of ray **18** is the rightmost ray projection which forms with the normal axis an angle denoted θ_x^-, and the projection of ray **17** is the leftmost ray projection which forms with the normal axis an angle denoted θ_x^+. When substrate **14** is held with the transverse axis directed upwards, the projection of ray **18** is viewed as the uppermost ray projection and the projection of ray **17** is viewed as the lowermost ray projection.

In exclusive representations, the longitudinal field-of-view, denoted Ω_y, is $[\theta_y^-, \theta_y^+]$ and the transverse field-of-view, denoted Ω_x is $[\theta_x^-, \theta_x^+]$. In the exemplified illustration of Figures 2b and 2c the projections θ_x^-, θ_y^- are measured anticlockwise from the normal axis (the *z* axis in Figures 2b and 2c), and the projections θ^+_x, θ^+_y are measured clockwise from the normal axis. Thus, according to the above convention, θ_x^-, θ_y^- have negative values and θ^+_x, θ^+_y have positive values, resulting in a

longitudinal field-of-view $\Omega_y = \theta_y^+ + |\theta_y^-|$, and a transverse field-of-view $\Omega_x = \theta_x^+ + |\theta_x^-|$, in inclusive representations.

Figure 2d schematically illustrates the field-of-view in a plane orthogonal to the normal axis of device **10** (parallel to the *x-y* plane, in the present coordinate system). Rays **17** and **18** are points on this plane. For the purpose of simplifying the presentation, the field-of-view is illustrated as a rectangle, and the straight light connecting the points is the diagonal of the rectangle. Rays **17** and **18** are referred to as the "lower-left" and "upper-right" light rays of the field-of-view, respectively.

It is appreciated that the field-of-view can also have a planar shape other than a rectangle, include, without limitation, a square, a circle and an ellipse. One of ordinary skills in the art, provided with the details described herein would know how to adjust the description for non-rectangle field-of-view.

In exclusive representation, the diagonal field-of-view of device **10** is given by $\Omega = [\theta^-, \theta^+]$, where θ^- the angle between ray **17** and a line intersecting ray **17** and being parallel to the normal axis, and θ^+ is the angle between ray **18** and a line intersecting ray **18** and being parallel to the normal axis. Figures 2e and 2f illustrate the diagonal field-of-view angles θ^- and θ^+ in planes containing ray **17** and ray **18**, respectively. The relation between $\theta^\pm$ and their projections $\theta_x^\pm$, $\theta_y^\pm$ are given by Equation 5 above with the substitutions $\phi_d \rightarrow \theta^\pm$, $\phi_{dx} \rightarrow \theta_x^\pm$ and $\phi_{dy} \rightarrow \theta_y^\pm$. Unless specifically stated otherwise, the term "field-of-view angle" refers to a diagonal angle, such as $\theta^\pm$.

The light rays arriving to device **10** can have one or more wavelength. When the light has a plurality of wavelengths, the shortest wavelength is denoted λ_B and the longest wavelength is denoted λ_R, and the range of wavelengths from λ_B to λ_R is referred to herein as the spectrum of the light.

Irrespectively of the number of different wavelengths of the light, when the light rays in the field-of-view impinge on element **13**, they are preferably redirected at an angle (defined relative to the normal) which is larger than the critical angle, such that upon striking the other surface of substrate **14**, all the light rays of the field-of-view experiences total internal reflection and propagate within substrate **14**.

In the representative illustration of Figures 2b-c, element **13** diffracts leftmost ray **17** and rightmost ray **18** into substrate **14** at diffraction angles denoted θ_d^+ and θ_d^-,

respectively. Shown in Figures 2b-c are $\theta_{yd}^{\pm}$ (Figure 2b) and $\theta_{xd}^{\pm}$ (Figure 2b), which are the projections of $\theta_d^{\pm}$ on the y-z plane and the x-z plane, respectively.

While propagating, the rays are reflected from the internal surfaces of substrate **14**. The Euclidian distance between two successive points on the internal surface of the substrate at which a particular light ray experiences total internal reflection is referred to as the "hop length" of the light ray and denoted by "h". The propagated light, after a few reflections within substrate **14**, generally along the longitudinal axis of device **10**, reaches output optical element **15** which redirects the light out of substrate **14**. Device **10** thus transmits at least a portion of the optical energy carried by each light ray between rays **17** and **18**. When the light rays within the field-of-view originate from an object which emits or reflects light, a viewer can position one or two eyes in front of element **15** to see a virtual image of the object.

As shown in Figure 2b, for a single impingement of a light ray on output element **15**, only a portion of the light energy exits substrate **14**. The remnant of each ray is redirected through an angle, which causes it, again, to experience total internal reflection from the other side of substrate **14**. After a first reflection, the remnant may re-strike element **15**, and upon each such re-strike, an additional part of the light energy exits substrate **14**. Thus, a light ray propagating in the substrate via total internal reflection exits the substrate in a form of a series of parallel light rays where the distance between two adjacent light rays in the series is h. Such series of parallel light rays corresponds to a collimated light beam exiting element **15**. Since more than one light ray exit as a series of parallel light rays, a beam of light passing through device **10** is expanded in a manner that the cross sectional area of the outgoing beam is larger than cross sectional area of the incoming beam.

According to a preferred embodiment of the present invention output optical element **15** is characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within the field-of-view is directed to a two-dimensional region **20** being at a predetermined distance Δz from light transmissive substrate **14**. More preferably, the planar dimensions of element **15** are selected such that the outgoing light beam enters region **20**.

To ensure entering of the outermost light ray or the entire outgoing light beam into region **20**, the length L_O of element **15** is preferably selected to be larger then a predetermined length threshold, $L_{O,\,min}$, and the width W_O of element **15** is preferably

selected to be larger then a predetermined width threshold, $W_{O,\ min}$. In various exemplary embodiments of the invention the length and width thresholds are given by the following expressions:

$$L_{O,\ min} = 2\ \Delta z\ \tan(\Omega_y/2)$$
$$W_{O,\ min} = 2\ \Delta z\ \tan(\Omega_x/2). \qquad \text{(EQ. 6)}$$

When device **10** is used for viewing a virtual image, the user may place his or her eye(s) within region **20** to view the virtual image. Thus, in this embodiment, region **20** is the "eye-box" of device **10**, and Δz is approximately the distance between the pupil(s) of the user to substrate **14**. The distance Δz is referred to herein as the characteristic eye-relief of device **10**. For transmitting an image to one eye, the length L_O and width W_O of element **15** are preferably about $L_{O,\ min} + O_p$, and about $W_{O,\ min} + O_p$, respectively, where O_p represents the diameter of the pupil and is typically about 3 millimeters. In various exemplary embodiments of the invention the eye-box is larger than the diameter of the pupil, so as to allow the user to relocate the eye within the eye-box while still viewing the entire virtual image. Thus, denoting the dimensions of region **20** by L_{EB} and W_{EB}, where L_{EB} is measured along the y axis and W_{EB} is measured along the x axis, the length and width of element **15** are preferably:

$$L_O = L_{O,\ min} + L_{EB}$$
$$W_O = W_{O,\ min} + W_{EB}, \qquad \text{(EQ. 7)}$$

where each of L_{EB} and W_{EB} is preferably larger than O_p, so as to allow the user to relocate the eye within region **20** while still viewing the entire field-of-view.

The dimensions of input optical element **13** are preferably selected to allow all light rays within the field-of-view to propagate in substrate **14** such as to impinge on the area of element **15**. In various exemplary embodiments of the invention the length L_I of input element **13** equals from about X to about $3X$ where X is preferably a unit hop-length characterizing the propagation of light rays within substrate **14**. Typically, X equals the hop-length of the light-ray with the minimal hop-length, which is one of the outermost light-rays in the field-of-view (ray **18** in the exemplified illustration of Figure 2b). When the light has a plurality of wavelengths, X is typically the hop-length of one of the outermost light-rays which has the shortest wavelength of the spectrum.

According to a preferred embodiment of the present invention the width W_O of element **15** is smaller than the width W_I of element **13**. W_I is preferably calculated

based on the relative arrangement of elements **13** and **15**. For example, in one embodiment, elements **13** and **15** are centrally aligned with respect to the transverse axis of device **10** (but laterally displaced along the longitudinal axis and optionally displaced also along the normal axis). In the present coordinate system this central alignment correspond to equal x coordinate for a central width line **130** (connecting half width points of element **13**) and a central width line **150** (connecting half width points of element **15**). In this embodiment, the relation between W_I is preferably given by the following expression:

$$W_I = 2\,(L_O + \Delta y)\tan\gamma + W_O, \qquad \text{(EQ. 8)}$$

where Δy is the lateral separation between element **13** and element **15** along the longitudinal axis of device **10** and γ is a predetermined angular parameter. Geometrically, γ is the angle formed between the longitudinal axis and a straight line connecting the corner of element **13** which is closest to element **15** and the corner of element **15** which is farthest from element **13** (see, *e.g.*, line **12** in Figure 2a).

Preferably, γ relates to the propagation direction of one or more of the outermost light rays of the field-of-view within the substrate, as projected on a plane parallel to the substrate. In various exemplary embodiments of the invention γ equals the angle formed between the longitudinal axis of the substrate and the propagation direction of an outermost light ray of the field-of-view, as projected on a plane parallel to the substrate.

Consider, for example, the "upper-right" light ray of the field-of-view impinging on element **13** at a field-of-view angle θ^- which is decomposed, according to the Cartesian coordinate system described above, into of angles θ_x^- (measured in the x-z plane) and θ_y^- (measured in the y-z plane). Using Equations 2 and 3 above, the corresponding components θ_{xd} and θ_{yd} of the diffraction angle θ_d can be calculated, *e.g.*, by selecting a value of 0° to θ_R. The propagation of the "upper-right" light ray in the substrate, can then be projected on a plane parallel to the substrate (the x-y plane in the present coordinate system), thereby forming a vector in the x-y plane. According to a preferred embodiment of the present invention γ is set to the angle formed between the projected vector and the y axis, which can be written in the form: $\gamma = \tan^{-1}[\sin(\theta_{xd})/\sin(\theta_{yd})]$. A typical value for the absolute value of γ is, without limitation, from about 6° to about 15°.

Thus, a viewer placing his or her eye in region **20** of dimensions $L_{EB} \times W_{EB}$, receives at least a portion of any light ray within the field-of-view, provided the distance between the eye and element **15** equals Δz or is smaller than Δz.

The preferred value for Δz is, without limitation, from about 15 millimeters to about 35 millimeters, the preferred value for Δy is, without limitation, from a few millimeters to a few centimeters, the preferred value for L_{EB} is, without limitation, from about 5 millimeters to about 13 millimeters, and the preferred value for W_{EB} is, without limitation, is from about 4 millimeters to about 9 millimeters. For a given field-of-view, selection of large Δz results in smaller eye-box dimensions L_{EB} and W_{EB}, as known in the art. Conversely, small Δz allows for larger eye-box dimensions L_{EB} and W_{EB}.

$L_{O,\,min}$ and $W_{O,\,min}$ are preferably calculated using Equation 6, and together with the selected dimensions of region **20** (L_{EB} and W_{EB}), the dimensions of element **15** (L_O and W_O) can be calculated using Equation 7.

Once L_O and W_O are calculated, the transverse dimension W_I of input element **13** is preferably calculated by selecting values for Δy and γ and using Equation 8. The longitudinal dimension L_I is generally selected from about 3 millimeters and about 15 millimeters.

In a preferred embodiment in which surfaces **23** and **24** of substrate **14** are substantially parallel, elements **13** and **15** can be designed, for a given spectrum, solely based on the value of θ^- and the value of the shortest wavelength λ_B. For example, when the optical elements are linear gratings, the period, D, of the gratings can be selected based on θ^- and λ_B, irrespectively of the optical properties of substrate **14** or any wavelength longer than λ_B.

According to a preferred embodiment of the present invention D is selected such that the ratio λ_B/D is from about 1 to about 2. A preferred expression for D is given by the following equation:

$$D = \lambda_B/[n_A(1 - \sin\theta^-)]. \qquad \text{(EQ. 9)}$$

It is appreciated that D, as given by Equation 9, is a maximal grating period. Hence, in order to accomplish total internal reflection D can also be smaller than $\lambda_B/[n_A(1-\sin\theta^-)]$.

Substrate **14** is preferably selected such as to allow light having any wavelength within the spectrum and any striking angle within the field-of-view to propagate in substrate **14** via total internal reflection.

According to a preferred embodiment of the present invention the refraction index of substrate **14** is larger than $\lambda_R/D + n_A\sin(\theta^+)$. More preferably, the refraction index, n_S, of substrate **14** satisfies the following equation:

$$n_S \geq [\lambda_R/D + n_A\sin(\theta^+)]/\sin(\alpha_D^{MAX}). \qquad \text{(EQ. 10)}$$

where α_D^{MAX} is the largest diffraction angle, *e.g.*, the diffraction angle of the light ray **17**. There are no theoretical limitations on α_D^{MAX}, except from a requirement that it is positive and smaller than 90 degrees. α_D^{MAX} can therefore have any positive value smaller than 90°. Various considerations for the value α_D^{MAX} are found in U.S. Patent No. 6,757,105, the contents of which are hereby incorporated by reference.

The thickness, t, of substrate **14** is preferably from about 0.1 mm to about 5 mm, more preferably from about 1 mm to about 3 mm, even more preferably from about 1 to about 2.5 mm. For multicolor use, t is preferably selected to allow simultaneous propagation of plurality of wavelengths, *e.g.*, $t > 10\,\lambda_R$. The width/length of substrate **14** is preferably from about 10 mm to about 100 mm. A typical width/length of the diffractive optical elements depends on the application for which device **10** is used. For example, device **10** can be employed in a near eye display, such as the display described in U.S. Patent No. 5,966,223, in which case the typical width/length of the diffractive optical elements is from about 5 mm to about 20 mm. The contents of U.S. Patent Application No. 60/716,533, which provides details as to the design of the diffractive optical elements and the selection of their dimensions, are hereby incorporated by reference.

For different viewing applications, such as the application described in U.S. Patent No. 6,833,955, the contents of which are hereby incorporated by reference, the length of substrate **14** can be 1000 mm or more, and the length of diffractive optical element **15** can have a similar size. When the length of the substrate is longer than 100 mm, then t is preferably larger than 5 millimeters. This embodiment is advantageous because it reduces the number of hops and maintains the substrate within reasonable structural/mechanical conditions.

Device **10** is capable of transmitting light having a spectrum spanning over at least 100 nm. More specifically, the shortest wavelength, λ_B, generally corresponds to a blue light having a typical wavelength of between about 400 to about 500 nm and the longest wavelength, λ_R, generally corresponds to a red light having a typical wavelength of between about 600 to about 700 nm.

As can be understood from the geometrical configuration illustrated in Figures 2b-c, the angles at which light rays **18** and **17** are redirected can differ. As the angles of redirection depend on the incident angles (see, *e.g.*, Equations 2-5 for the case of diffraction), the allowed clockwise (θ^+) and anticlockwise (θ^-) field-of-view angles, are also different. Thus, device **10** supports transmission of asymmetric field-of-view in which, say, the clockwise field-of-view angle is greater than the anticlockwise field-of-view angle. The difference between the absolute values of the clockwise and anticlockwise field-of-view angles can reach more than 70 % of the total field-of-view.

This asymmetry can be exploited in accordance with various exemplary embodiments of the present invention, to enlarge the field-of-view of optical device **10**. According to a preferred embodiment of the present invention, a light-transmissive substrate can be formed with at least one input optical element and two or more output optical elements. The input optical element(s) serve for redirecting the light into the light-transmissive substrate in a manner such that different portions of the light, corresponding to different partial field-of-views, propagate within the substrate in different directions to thereby reach the output optical elements. The output optical elements redirect the different portions of the light out of the light-transmissive substrate.

In accordance with the present embodiments, the planar dimensions of the output and/or input optical elements can be selected to facilitate the transmission of the partial field-of-views. The output optical elements can also be designed and constructed such that the redirection of the different portions of the light is in complementary manner.

The terms "complementarily" or "complementary," as used herein in conjunction with a particular observable or quantity (*e.g.*, field-of-view, image, spectrum), refer to a combination of two or more overlapping or non-overlapping parts of the observable or quantity, which combination provides the information required for substantially reconstructing the original observable or quantity.

In various exemplary embodiments of the invention, the optical elements of the optical relay device are designed to transmit an image covering a wide field-of-view to both eyes of the user (*e.g.*, using one input element and two output elements). Preferably, the optical relay device of the present embodiments is characterized by a diagonal field-of-view of at least 16° (corresponding to longitudinal field-of-view of about 12°), more preferably at least 20° (corresponding to longitudinal field-of-view of about 15°), more preferably at least 24° (corresponding to longitudinal field-of-view of about 18°), more preferably at least 32° (corresponding to longitudinal field-of-view of about 24°). The optical elements are preferably located at fixed locations on the light transmissive substrate, but provide the image for any interpupillary distance from a minimal value denoted IPD_{min} to a maximal value denoted IPD_{max}.

The advantage of the present embodiments is that any user with an interpupillary distance IPD satisfying $IPD_{min} \leq IPD \leq IPD_{max}$ can use the device to view the entire image without having to adjust the size of the device or the separation between the optical elements. The range of IPD in western society grown-ups is from about 53 mm to about 73 mm. Children have further smaller IPD. Other human races generally have different ranges of IPD. A preferred value for IPD_{min} is from about 5mm to about 20 millimeters less than the selected value for IPD_{max}, more preferably from about 5mm to about 10 millimeters less than the selected value for IPD_{max}, and the two values are preferably selected within the range of human IPD as described above.

Any number of input/output optical elements can be used. Additionally, the number of input optical elements and the number of output optical elements may be different, as two or more output optical elements may share the same input optical element by optically communicating therewith. The input and output optical elements can be formed on a single substrate or a plurality of substrates, as desired. For example, in one embodiment, the input and output optical elements comprise linear diffraction gratings of identical periods, formed on a single substrate, preferably in a parallel orientation.

If several input/output optical elements are formed on the same substrate, as in the above embodiment, they can engage any side of the substrate, in any combination.

One ordinarily skilled in the art would appreciate that this corresponds to any combination of transmissive and reflective optical elements. Thus, for example,

suppose that there is one input optical element, formed on surface **23** of substrate **14** and two output optical elements formed on surface **24**. Suppose further that the light impinges on surface **23** and it is desired to diffract the light out of surface **24**. In this case, the input optical element and the two output optical elements are all transmissive, so as to ensure that entrance of the light through the input optical element, and the exit of the light through the output optical elements. Alternatively, if the input and output optical elements are all formed on surface **23**, then the input optical element remain transmissive, so as to ensure the entrance of the light therethrough, while the output optical elements are reflective, so as to reflect the propagating light at an angle which is sufficiently small to couple the light out. In such configuration, light can enter the substrate through the side opposite the input optical element, be diffracted in reflection mode by the input optical element, propagate within the light transmissive substrate in total internal diffraction and be diffracted out by the output optical elements operating in a transmission mode.

Reference is now made to Figures 3a-b which are schematic illustrations of a perspective view (Figure 3a) and a side view (Figure 3b) of device **10**, in a preferred embodiment in which one input optical element **13** and two output optical elements **15** and **19** are employed. In this embodiment, device **10** can be used as a binocular device for transmitting light to a first eye **25** and a second eye **30** of a user characterized by an interpupillary distance, IPD.

In Figure 3b, first **15** and second **19** output optical elements are formed, together with input optical element **13**, on surface **23** of substrate **14**. However, as stated, this need not necessarily be the case, since, for some applications, it may be desired to form the input/output optical elements on any of the surfaces of substrate **14**, in an appropriate transmissive/reflective combination. Wavefront propagation within substrate **14**, according to various exemplary embodiments of the present invention, is further detailed hereinunder with reference to Figures 4a-b.

Element **13** preferably redirects the incoming light into substrate **14** in a manner such that different portions of the light, corresponding to different partial fields-of-view, propagate in different directions within substrate **14**. In the configuration exemplified in Figures 3a-b, element **13** redirects light rays within one asymmetric partial field-of-view, designated by reference numeral **26**, leftwards to impinge on element **15**, and another asymmetric partial field-of-view, designated by

reference numeral **32**, to impinge on element **19**. Elements **15** and **19** complementarily redirect the respective portions of the light, or portions thereof, out of substrate **14**, to provide first eye **25** with partial field-of-view **26** and second eye **30** with partial field-of-view **32**.

Partial field-of-views **26** and **32** form together the field-of-view **27** of device **10**. Similarly to the embodiments in which one output optical element is employed (see, *e.g.*, Figures 2a-c) elements **15** and **19** are characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within partial field-of-view **26** is directed to two-dimensional region **20**, and at least a portion of one or more outermost light rays within partial field-of-view **32** is directed to another two-dimensional region **22**. This can be achieved by selecting the lengths and widths of elements **15** and **19** to be larger then predetermined length and width thresholds, as described above (see Equations 6-7).

Preferably, but not obligatorily, the planar dimensions of region **20** equal the planar dimensions of region **22**. Thus, the planar dimensions of each of regions **20** and **22** as well as the distance Δz are preferably within the aforementioned ranges.

In various exemplary embodiments of the invention the lateral separation between the longitudinal centers of regions **20** and **22** is at least 40 millimeters. Preferably, the lateral separation between the longitudinal centers of regions **20** and **22** is less than 80 millimeters. According to a preferred embodiment of the present invention the planar dimensions of elements **15** and **19** are selected such that the portions of outermost light rays are respectively directed to regions **20** and **22**, for any lateral separation between the regions which is larger than 40 millimeters and smaller than 80 millimeters.

When device **10** is used for transmitting light to the eyes of the user, the planar dimensions of elements **15** and **19** are preferably selected such that eyes **25** and **30** are respectively provided with partial field-of-views **26** and **32** for any interpupillary distance IPD satisfying $IPD_{min} \leq IPD \leq IPD_{max}$.

This is preferably ensured by selecting the lengths L_{EB} of regions **20** and **22** according to the following weak inequality:

$$L_{EB} \geq (IPD_{max} - IPD_{min})/2. \qquad \text{(EQ. 11)}$$

Once L_{EB} is selected to satisfy Equation 11, the lengths and widths of output elements **15** and **19** can be set according to Equations 7 substantially as described

hereinabove. According to a preferred embodiment of the present invention the longitudinal center of each of elements **15** and **19** is located at a distance of $(IPD_{max} + IPD_{min})/4$ from the longitudinal center of element **13**.

The width W_I of element **13** is preferably larger than width of each of elements **15** and **19**. The calculation of W_I is preferably, but not obligatorily, performed using a procedure similar to the procedure described above, see Equation **8**. When it is desired to manufacture a symmetric optical relay, the same planar dimensions $L_O \times W_O$ are used for both output elements **15** and **19**, and the same lateral separation Δy is used between elements **13** and **15** and between elements **13** and **19**. In this case, the width W_I of the input element can be set according to Equation **8** using the angular parameter γ as described above. Equation **8** can also be used in for configuration in which the lateral separation between elements **13** and **15** differs from the lateral separation between elements **13** and **19**. In this case the value of Δy which is used in the calculation is preferably set to the larger of the two lateral separations.

When device **10** is used for transmitting an image **34**, field-of-view **27** preferably includes substantially all light rays originated from image **34**. Partial fields-of-view **26** and **32** can therefore correspond to different parts of image **34**, which different parts are designated in Figure 3b by numerals **36** and **38**. Thus, as shown in Figure 3b, there is at least one light ray **42** which enters device **10** via element **13** and exits device **10** via element **19** but not via element **15**. Similarly, there is at least one light ray **43** which enters device **10** via element **13** and exits device **10** via element **15** but not via element **19**.

Generally, the partial field-of-views, hence also the parts of the image arriving to each eye depend on the wavelength of the light. Therefore, it is not intended to limit the scope of the present embodiments to a configuration in which part **36** is viewed by eye **25** and part **38** viewed by eye **30**. In other words, for different wavelengths, part **36** is viewed by eye **30** and part **38** viewed by eye **25**. For example, when the image is constituted by a light having three colors: red, green and blue, device **10** can be constructed such that eye **25** sees part **38** for the blue light and part **36** for the red light, while eye **30** sees part **36** for the blue light and part **38** for the red light. In such configuration, both eyes see an almost symmetric field-of-view for the green light. Thus, for every color, the two partial fields-of-view compliment each other.

The human visual system is known to possess a physiological mechanism capable of inferring a complete image based on several parts thereof, provided sufficient information reaches the retinas. This physiological mechanism operates on monochromatic as well as chromatic information received from the rod cells and cone cells of the retinas. Thus, in a cumulative nature, the two asymmetric field-of-views, reaching each individual eye, form a combined field-of-view perceived by the user, which combined field-of-view is wider than each individual asymmetric field-of-view.

According to a preferred embodiment of the present invention, there is a predetermined overlap between first **26** and second **32** partial fields-of-view, which overlap allows the user's visual system to combine parts **36** and **38** of image **34**, thereby to perceive the image, as if it has been fully observed by each individual eye.

For example, the optical elements can be constructed such that the exclusive representations of partial fields-of-view **26** and **32** are, respectively, $[-\alpha, \beta]$ and $[-\beta, \alpha]$, resulting in a symmetric combined field-of-view **27** of $[-\beta, \beta]$. It will be appreciated that when $\beta >> \alpha > 0$, the combined field-of-view is considerably wider than each of the asymmetric field-of-views. Device **10** is capable of transmitting a field-of-view of at least 20 degrees, more preferably at least 30 degrees most preferably at least 40 degrees, in inclusive representation.

When the image is a multicolor image having a spectrum of wavelengths, different sub-spectra correspond to different, wavelength-dependent, asymmetric partial field-of-views, which, in different combinations, form different wavelength-dependent combined fields-of-view. For example, a red light can correspond to a first red asymmetric partial field-of-view, and a second red asymmetric partial field-of-view, which combine to a red combined field-of-view. Similarly, a blue light can correspond to a first blue asymmetric partial field-of-view, and a second blue asymmetric partial field-of-view, which combine to a blue combined field-of-view, and so on. Thus, a multicolor configuration is characterized by a plurality of wavelength-dependent combined field-of-views. According to a preferred embodiment of the present invention the optical elements are designed and constructed so as to maximize the overlap between two or more of the wavelength-dependent combined field-of-views.

In terms of spectral coverage, the design of device **10** is preferably as follows: element **15** provides eye **25** with, say, a first sub-spectrum which originates from part

36 of image **34**, and a second sub-spectrum which originates from part **38** of image **34**. Element **19** preferably provides the complementary information, so as to allow the aforementioned physiological mechanism to infer the complete spectrum of the image. Thus, element **19** preferably provides eye **30** with the first sub-spectrum originating from part **38**, and the second sub-spectrum originating from part **36**.

Ideally, a multicolor image is a spectrum as a function of wavelength, measured at a plurality of image elements. This ideal input, however, is rarely attainable in practical systems. Therefore, the present embodiment also addresses other forms of imagery information. A large percentage of the visible spectrum (color gamut) can be represented by mixing red, green, and blue colored light in various proportions, while different intensities provide different saturation levels. Sometimes, other colors are used in addition to red, green and blue, in order to increase the color gamut. In other cases, different combinations of colored light are used in order to represent certain partial spectral ranges within the human visible spectrum.

In a different form of color imagery, a wide-spectrum light source is used, with the imagery information provided by the use of color filters. The most common such system is using white light source with cyan, magenta and yellow filters, including a complimentary black filter. The use of these filters could provide representation of spectral range or color gamut similar to the one that uses red, green and blue light sources, while saturation levels are attained through the use of different optical absorptive thickness for these filters, providing the well known "grey levels."

Thus, the multicolored image can be displayed by three or more channels, such as, but not limited to, Red-Green-Blue (RGB) or Cyan-Magenta-Yellow-Black (CMYK) channels. RGB channels are typically used for active display systems (*e.g.*, CRT or OLED) or light shutter systems (*e.g.*, Digital Light Processing™ (DLP™) or LCD illuminated with RGB light sources such as LEDs). CMYK images are typically used for passive display systems (*e.g.*, print). Other forms are also contemplated within the scope of the present invention.

When the multicolor image is formed from a discrete number of colors (*e.g.*, an RGB display), the sub-spectra can be discrete values of wavelength. For example, a multicolor image can be provided by an OLED array having red, green and blue organic diodes (or white diodes used with red, green and blue filters) which are viewed by the eye as continues spectrum of colors due to many different combinations of

relative proportions of intensities between the wavelengths of light emitted thereby. For such images, the first and the second sub-spectra can correspond to the wavelengths emitted by two of the blue, green and red diodes of the OLED array, for example the blue and red. Device **10** can be constructed such that, say, eye **30** is provided with blue light from part **36** and red light from part **38** whereas eye **25** is provided with red light from part **36** and blue light from part **38**, such that the entire spectral range of the image is transmitted into the two eyes and the physiological mechanism reconstructs the image.

The light arriving at the input optical element of device **10** is preferably collimated. In case the light is not collimated, a collimator **44** can be positioned on the light path between image **34** and the input element.

Collimator **44** can be, for example, a converging lens (spherical or non spherical), an arrangement of lenses and the like. Collimator **44** can also be a diffractive optical element, which may be spaced apart, carried by or formed in substrate **14**. A diffractive collimator may be positioned either on the entry surface of substrate **14**, as a transmissive diffractive element or on the opposite surface as a reflective diffractive element.

Following is a description of the principles and operations of optical device **10**, in the preferred embodiments in which device **10** comprises one input optical element and two output optical elements.

Reference is now made to Figures 4a-b which are schematic illustrations of wavefront propagation within substrate **14**, according to preferred embodiments in which diffractive elements are employed. Shown in Figures 4a-b are four principal light rays, **51**, **52**, **53** and **54**, respectively emitted from four points, **A**, **B**, **C** and **D**, of image **34**. The illustrations in Figures 4a-b lie in the *y-z* plane. The projections of the incident angles of rays **51**, **52**, **53** and **54** onto the *y-z* plane relative to the normal axis are denoted α_I^{--}, α_I^{-+}, α_I^{+-} and α_I^{++}, respectively. As will be appreciated by one of ordinary skill in the art, the first superscript index refer to the position of the respective ray relative to the center of the field-of-view, and the second superscript index refer to the position of the respective ray relative to the normal from which the angle is measured, according to the aforementioned sign convention.

It is to be understood that this sign convention cannot be considered as limiting, and that one ordinarily skilled in the art can easily practice the present invention employing an alternative convention.

Similar notations will be used below for diffraction angles of the rays, with the subscript D replacing the subscript I. Denoting the superscript indices by a pair i, j, an incident angle is denoted generally as α_I^{ij}, and a diffraction angle is denoted generally as α_D^{ij}, where $i\,j$ = "$--$", "$-+$", "$+-$" or "$--$". The relation between each incident angle, α_I^{ij}, and its respective diffraction angle, α_D^{ij}, is given by Equation 4, above, with the replacements $\phi_{iy} \rightarrow \alpha_I^{ij}$, and $\phi_{dy} \rightarrow \alpha_D^{ij}$.

Points **A** and **D** represent the left end and the right end of image **34**, and points **B** and **C** are located between points **A** and **D**. Thus, rays **51** and **53** are the leftmost and the rightmost light rays of a first asymmetric field-of-view, corresponding to a part **A-C** of image **34**, and rays **52** and **54** are the leftmost and the rightmost light rays of a second asymmetric field-of-view corresponding to a part **B-D** of image **34**. In angular notation, the first and second asymmetric field-of-views are, respectively, $[\alpha_I^{--}, \alpha_I^{+-}]$ and $[\alpha_I^{-+}, \alpha_I^{++}]$ (exclusive representations). Note that an overlap field-of-view between the two asymmetric field-of-views is defined between rays **52** and **53**, which overlap equals $[\alpha_I^{-+}, \alpha_I^{+-}]$ and corresponds to an overlap **B-C** between parts **A-C** and **B-D** of image **34**.

In the configuration shown in Figures 4a-b, lens **45** magnifies image **34** and collimates the wavefronts emanating therefrom. For example, light rays **51-54** pass through a center of lens **45**, impinge on substrate **14** at angles α_I^{ij} and diffracted by input optical element **13** into substrate **14** at angles α_D^{ij}. For the purpose of a better understanding of the illustrations in Figures 4a-b, only two of the four diffraction angles (to each side) are shown in each figure, where Figure 4a shows the diffraction angles to the right of rays **51** and **53** (angles α_D^{+-} and α_D^{--}), and Figure 4b shows the diffraction angles to the right of rays **52** and **54** (angles α_D^{-+} and α_D^{++}).

Each diffracted light ray experiences a total internal reflection upon impinging on the inner surfaces of substrate **14** if $|\alpha_D^{ij}|$, the absolute value of the diffraction angle, is larger than the critical angle α_c. Light rays with $|\alpha_D^{ij}| < \alpha_c$ do not experience a total internal reflection hence escape from substrate **14**. Generally, because input optical element **13** diffracts the light both to the left and to the right, a light ray may, in

principle, split into two secondary rays each propagating in an opposite direction within substrate **14**, provided the diffraction angle of each of the two secondary rays is larger than α_c. To ease the understanding of the illustrations in Figures 4a-b, secondary rays diffracting leftward and rightward are designated by a single and double prime, respectively.

Reference is now made to Figure 4a showing a particular and preferred embodiment in which $|\alpha_D^{-+}| = |\alpha_D^{+-}| = \alpha_c$. Shown in Figure 4a are rightward propagating rays **51"** and **53"**, and leftward propagating rays **52'** and **54'**. Hence, in this embodiment, element **13** split all light rays between ray **51** and ray **52** into two secondary rays, a left secondary ray, impinging on the inner surface of substrate **14** at an angle which is smaller than α_c, and a right secondary ray, impinging on the inner surface of substrate **14** at an angle which is larger than α_c. Thus, light rays between ray **51** and ray **52** can only propagate rightward within substrate **14**. Similarly, light rays between ray **53** and ray **54** can only propagate leftward. On the other hand, light rays between rays **52** and **53**, corresponding to the overlap between the asymmetric field-of-views, propagate in both directions, because element **13** split each such ray into two secondary rays, both impinging the inner surface of substrate **14** at an angle larger than the critical angle, α_c.

Thus, light rays of the asymmetrical field-of-view defined between rays **51** and **53** propagate within substrate **14** to thereby reach second output optical element **19** (not shown in Figure 4a), and light rays of the asymmetrical field-of-view defined between rays **52** and **54** propagate within substrate **14** to thereby reach first output optical element **15** (not shown in Figure 4a).

In another embodiment, illustrated in Figure 4b, the light rays at the largest entry angle split into two secondary rays, both with a diffraction angle which is larger than α_c, hence do not escape from substrate **14**. However, whereas one secondary ray experience a few reflections within substrate **14**, and thus successfully reaches its respective output optical element (not shown), the diffraction angle of the other secondary ray is too large for the secondary ray to impinge the other side of substrate **14**, so as to properly propagate therein and reach its respective output optical element.

Specifically shown in Figure 4b are original rays **51**, **52**, **53** and **54** and secondary rays **51'**, **52"**, **53'** and **54"**. Ray **54** splits into two secondary rays, ray **54'** (not shown) and ray **54"** diffracting leftward and rightward, respectively. However,

whereas rightward propagating ray **54''** diffracted at an angle α_D^{++} experiences a few reflection within substrate **14** (see Figure 4b), leftward propagating ray **54'** either diffracts at an angle which is too large to successfully reach element **15**, or evanesces.

Similarly, ray **52** splits into two secondary rays, **52'** (not shown) and **52''** diffracting leftward and rightward, respectively. For example, rightward propagating ray **52''** diffracts at an angle $\alpha_D^{-+} > \alpha_c$. Both secondary rays diffract at an angle which is larger than α_c, experience one or a few reflections within substrate **14** and reach output optical element **15** and **19** respectively (not shown). In the case that α_D^{-+} is the largest angle for which the diffracted light ray will successfully reach the optical output element **19**, all light rays emitted from part **A-B** of the image do not reach element **19** and all light rays emitted from part **B-D** successfully reach element **19**. Similarly, if angle α_D^{+-} is the largest angle (in absolute value) for which the diffracted light ray will successfully reach optical output element **15**, then all light rays emitted from part **C-D** of the image do not reach element **15** and all light rays emitted from part **A-C** successfully reach element **15**.

Thus, light rays of the asymmetrical field-of-view defined between rays **51** and **53** propagate within substrate **14** to thereby reach output optical element **15**, and light rays of the asymmetrical field-of-view defined between rays **52** and **54** propagate within substrate **14** to thereby reach output optical element **19**.

Any of the above embodiments can be successfully implemented by a judicious design of the monocular devices, and, more specifically the input/output optical elements and the substrate.

For example, as stated, the input and output optical elements can be linear diffraction gratings having identical periods and being in a parallel orientation. This embodiment is advantageous because it is angle-preserving. Specifically, the identical periods and parallelism of the linear gratings ensure that the relative orientation between light rays exiting the substrate is similar to their relative orientation before the impingement on the input optical element. Consequently, light rays emanating from a particular point of the overlap part **B-C** of image **34**, hence reaching both eyes, are parallel to each other. Thus, such light rays can be viewed by both eyes as arriving from the same angle in space. It will be appreciated that with such configuration viewing convergence is easily obtained without eye-strain or any other inconvenience

to the viewer, unlike the prior art binocular devices in which relative positioning and/or relative alignment of the optical elements is necessary.

According to a preferred embodiment of the present invention the period, D, of the gratings and/or the refraction index, n_S, of the substrate can be selected so to provide the two asymmetrical field-of-views, while ensuring a predetermined overlap therebetween. This can be achieved in more than one way.

Hence, in one embodiment, a ratio between the wavelength, λ, of the light and the period D is larger than or equal a unity:

$$\lambda/D \geq 1. \qquad \text{(EQ. 12)}$$

This embodiment can be used to provide an optical device operating according to the aforementioned principle in which there is no mixing between light rays of the non-overlapping parts of the field-of-view (see Figure 4a).

In another embodiment, the ratio λ/D is smaller than the refraction index, n_S, of the substrate. More specifically, D and n_S can be selected to comply with the following inequality:

$$D > \lambda/(n_S\, p), \qquad \text{(EQ. 13)}$$

where p is a predetermined parameter which is smaller than 1.

The value of p is preferably selected so as to ensure operation of the device according to the principle in which some mixing is allowed between light rays of the non-overlapping parts of the field-of-view, as further detailed hereinabove (see Figure 4b). This can be done for example, by setting $p = \sin(\alpha_D^{MAX})$, where (α_D^{MAX}) is a maximal diffraction angle. Because there are generally no theoretical limitations on α_D^{MAX} (apart from a requirement that its absolute value is smaller than 90°), it may be selected according to any practical considerations, such as cost, availability or geometrical limitations which may be imposed by a certain miniaturization necessity. Hence, in one embodiment, further referred to herein as the "at least one hop" embodiment, α_D^{MAX} is selected so as to allow at least one reflection within a predetermined distance x which may vary from about 30 mm to about 80 mm.

For example, for a glass substrate, with an index of refraction of $n_S = 1.5$ and a thickness of 2 mm, a single total internal reflection event of a light having a wavelength of 465 nm within a distance x of 34 mm, corresponds to $\alpha_D^{MAX} = 83.3°$.

In another embodiment, further referred to herein as the "flat" embodiment, α_D^{MAX} is selected so as to reduce the number of reflection events within the substrate, *e.g.*, by imposing a requirement that all the diffraction angles will be sufficiently small, say, below 80°.

In an additional embodiment, particularly applicable to those situations in the industry in which the refraction index of the substrate is already known (for example when device **10** is intended to operate synchronically with a given device which includes a specific substrate), Equation 13 may be inverted to obtain the value of p hence also the value of $\alpha_D^{MAX} = \sin^{-1}p$.

As stated, device **10** can transmit light having a plurality of wavelengths. According to a preferred embodiment of the present invention, for a multicolor image the gratings period is preferably selected to comply with Equation 12, for the shortest wavelength, and with Equation 13, for the longest wavelength. Specifically:

$$\lambda_R/(n_s\, p) \leq D \leq \lambda_B\,, \qquad \text{(EQ. 14)}$$

where λ_B and λ_R are, respectively, the shortest and longest wavelengths of the multicolor spectrum. Note that it follows from Equation 12 that the index of refraction of the substrate should satisfy, under these conditions, $n_s\, p \geq \lambda_R/\lambda_B$.

The grating period can also be smaller than the sum $\lambda_B + \lambda_R$, for example:

$$D = \frac{\lambda_B + \lambda_R}{n_S \sin(\alpha_D^{MAX}) + n_A}\,. \qquad \text{(EQ. 15)}$$

As stated, when a light ray propagates in the substrate via total internal reflection, typically only a portion of the light energy exits the substrate while the remnant of the ray is reflected back into the substrate. When the output optical element is diffractive, this corresponds to a diffraction efficiency of less than 100 %. The diffraction efficiency is defined as the fraction of light energy being diffracted by the diffractive optical element.

For a uniform diffraction efficiency of the output elements, each light ray of the series exits with a lower intensity compared to the preceding light ray. For example, suppose that the diffraction efficiency of the output grating for a particular wavelength is 50 % (meaning that for this wavelength 50 % of the light energy is diffracted at each diffraction occurrence). In this case, the first light ray of the series carries 50 % of the original energy, the second light ray of the series carries less than

25 % of the original energy and so on. This results in a non-uniform light output across the output grating.

The present embodiments successfully provide an optical element with a grating designed to provide a predetermined light profile. Generally, a profile of light refers to an optical characteristic (intensity, phase, wavelength, brightness, hue, saturation, *etc.*) or a collection of optical characteristics of a light beam.

A light beam is typically described as a plurality of light rays which can be parallel, in which case the light beam is said to be collimated, or non-parallel, in which case the light beam is said to be non-collimated.

A light ray is mathematically described as a one-dimensional mathematical object. As such, a light ray intersects any surface which is not parallel to the light ray at a point. A light beam therefore intersects a surface which is not parallel to the beam at a plurality of points, one point for each light ray of the beam. The profile of light is the optical characteristic of the locus of all such intersecting points. In various exemplary embodiments of the invention the profile comprises the intensity of the light and, optionally, one or more other optical characteristics.

Typically, but not obligatorily, the profile of the light beam is measured at a planar surface which is substantially perpendicular to the propagation direction of the light.

A profile relating to a specific optical characteristic is referred to herein as a specific profile and is termed using the respective characteristic. Thus, the term "intensity profile" refers to the intensity of the locus of all the intersecting points, the term "wavelength profile" refers to the wavelength of the locus of all the intersecting points, and so on.

Reference is now made to Figures 5a-b which are schematic illustration of a fragmentary top view (Figure 5a) and a fragmentary side view (Figure 5b) of device **10** in the preferred embodiment in which one or more of its diffractive optical elements comprise a grating. The following description is for output element **15**, but one of ordinary skills in the art, provided with the details described herein would know how to adjust the description for the case of other diffractive elements of device **10**. Preferably, but not obligatorily, all the diffractive elements of device **10** are manufactured according to the principles described below.

According to a preferred embodiment of the present invention element **15** has a periodic linear structure **11** in one or more directions. In the representative illustration of Figure 5a, the periodic linear structure is along the *y* direction. Shown in Figure 5b is a light ray **16** which propagates within substrate **14** via total internal reflection and impinge on the grating of element **15**. Element **15** diffracts ray **16** out of substrate **14** to provide a light beam **21** having a predetermined profile. Preferably, element **15** is described by a non-uniform diffraction efficiency function.

The term "non-uniform," when used in conjunction with a particular observable characterizing the grating (*e.g.*, diffraction efficiency function, duty cycle, modulation depth), refers to variation of the particular observable along at least one direction, and preferably along the same direction as the periodic linear structure (*e.g.*, the *y* direction in the exemplified illustration of Figure 5a).

The diffraction efficiency function returns the local diffraction efficiency (*i.e.*, the diffraction efficiency of a particular region) of the grating and can be expressed in terms of percentage relative to the maximal diffraction efficiency of the grating. For example, at a point on the grating at which the diffraction efficiency function returns the value of, say, 50 %, the local diffraction efficiency of the grating is 50 % of the maximal diffraction efficiency. In various exemplary embodiments of the invention the diffraction efficiency function is a monotonic function over the grating.

The term "monotonic function", as used herein, has the commonly understood mathematical meaning, namely, a function which is either non-decreasing or non-increasing. Mathematically, a function $f(x)$ is said to be monotonic over the interval $[a, b]$ if $f(x_1) \geq f(x_2)$ for any $x_1 \in [a, b]$ and $x_2 \in [a, b]$ satisfying $x_1 > x_2$, or if $f(x_1) \leq f(x_2)$ for any such x_1 and x_2.

In various exemplary embodiments of the invention light beam **21** has a substantially uniform intensity profile for a predetermined range of wavelengths.

As used herein, "substantially uniform intensity profile" refers to an intensity which varies by less than 2 % per millimeter, more preferably less than 1 % per millimeter.

A "predetermined range of wavelengths" is characterized herein by a central value and an interval. Preferably the predetermined range of wavelengths extends from about 0.7 λ to about 1.3 λ, more preferably from about 0.85 λ to about 1.15 λ, where λ is the central value characterizing the range.

Thus, the non-uniform diffraction efficiency function is selected such that when a light ray impinges on grating a plurality of times, a predetermined and substantially constant fraction of the energy of light is diffracted at each impingement.

This can be achieved when the diffraction efficiency function returns a harmonic series ($1/k$, k=1, 2, ...) at the intersection points between the light ray and the grating. In the exemplified embodiment of Figure 5b ray **16** experiences four diffractions along element **15**. The diffraction points are designated by roman numerals I, II, III and IV. In this example, the diffraction efficiency function preferably returns the value 25 % at point I, 33 % at point II, 50 % at point III and 100 % at point IV. For illustrative purposes, reflected light rays of different optical energy are shown in Figure 5b using different types of lines: solid lines, for light rays carrying 100 % of the original optical energy, dotted lines (75 %), dashed lines (50 %) and dot-dashed lines (25 %). Each of the four diffractions thus results in an emission of 25 % of the original optical energy of the light ray, and a substantially uniform intensity profile of the light across element **15** is achieved.

The non-uniform diffraction efficiency function of element **15** can be achieved in more than one way.

In one embodiment, linear structure **11** of element **15** is characterized by non-uniform duty cycle selected in accordance with the desired diffraction efficiency function.

As used herein, "duty cycle" is defined as the ratio of the width, W, of a ridge in the grating to the period D.

A representative example of element **10** in the preferred embodiment in which element **15** has non-uniform duty cycle is illustrated in Figure 6. As shown element **15** comprises a plurality of ridges **62** and grooves **64**. In the exemplified illustration of Figure 6, the ridges and grooves of the grating form a shape of a square wave. Such grating is referred to as a "binary grating". Other shapes for the ridges and grooves are also contemplated. Representative examples include, without limitation, triangle, saw tooth and the like.

Figure 6 exemplifies a preferred embodiment in which element **15** comprises different sections, where in each section the ridges have a different width. In a first section, designated **15a**, the width S_1 of the ridges equals 0.5 D, hence the duty cycle is 0.5; in a second section, designated **15b**, the width S_2 of the ridges equals 0.25 D,

hence the duty cycle is 0.25; and in a third section, designated **15c**, the width S_3 of the ridges equals $0.75\ D$, hence the duty cycle is 0.75.

As demonstrated in the Examples section that follows (see Figures 11a-d) the diffraction efficiency significantly depends on the value of the duty cycle. Thus, a non-uniform diffraction efficiency function can be achieved using a non-uniform duty cycle. Additionally, Figures 11a-d demonstrate that the relation between the diffraction efficiency and the duty cycle depends on the wavelength of the light. By judicious selection of the duty cycle at each region of element **15**, a predetermined profile (intensity, wavelength, *etc.*) can be obtained.

Linear grating having a non-uniform duty cycle suitable for the present embodiments is preferably fabricated utilizing a technology characterized by a resolution of 50-100 nm. For example, element **15** can be formed on a light transmissive substrate by employing a process in which electron beam lithography is followed by etching. A process suitable for forming grating having a non-uniform duty cycle according to embodiments of the present invention may be similar to and/or be based on the teachings of U.S. Patent Application No. 11/505,866, assigned to the common assignee of the present invention and fully incorporated herein by reference.

An additional embodiment for achieving non-uniform diffraction efficiency function includes a linear structure characterized by non-uniform modulation depth.

Figure 7 exemplifies a preferred embodiment in which element **15** comprises different sections, where in each section the ridges and grooves of element **15** are characterized by a different modulation depth. The three sections **15a**, **15b** and **15c** have identical duty cycles S/D, but their modulation depths differ. The modulation depth of sections **15a**, **15b** and **15c** are denoted δ_1, δ_2 and δ_3, respectively.

It is demonstrated in the Examples section that follows (see Figures 12a-b) that the diffraction efficiency significantly depends on the value of the modulation depth, and that the relation between the diffraction efficiency and the modulation depth depends on the wavelength of the light. A non-uniform diffraction efficiency function can therefore be achieved using a non-uniform modulation depth. By judicious selection of the modulation depth of element **15** at each region of element **15**, a predetermined profile can be obtained.

In another embodiment, illustrated in Figure 8, the linear structure of the grating is characterized by non-uniform modulation depth and non-uniform duty-

cycle, where the non-uniform duty cycle is selected in combination with the non-uniform modulation depth to provide the desired non-uniform diffraction efficiency function. As will be appreciated by one ordinarily skilled in the art, the combination between non-uniform duty cycle and non-uniform modulation depth significantly improves the ability to accurately design the grating in accordance with the required profile, because such combination increases the number of degrees of freedom available to the designer.

According to an additional aspect of the present invention there is provided a system **100** for providing an image to a user in a wide field-of-view.

Reference is now made to Figure 9 which is a schematic illustration of system **100**, which, in its simplest configuration, comprises optical relay device **10** for transmitting image **34** into first eye **25** and second eye **30** of the user, and an image generating system **121** for providing optical relay device **10** with collimated light constituting the image.

Image generating system **121** can be either analog or digital. An analog image generating system typically comprises a light source **127**, at least one image carrier **29** and a collimator **44**. Collimator **44** serves for collimating the input light, if it is not already collimated, prior to impinging on substrate **14**. In the schematic illustration of Figure 9, collimator **44** is illustrated as integrated within system **121**, however, this need not necessarily be the case since, for some applications, it may be desired to have collimator **44** as a separate element. Thus, system **121** can be formed of two or more separate units. For example, one unit can comprise the light source and the image carrier, and the other unit can comprise the collimator. Collimator **44** is positioned on the light path between the image carrier and the input element of device **10**.

Any collimating element known in the art may be used as collimator **44**, for example a converging lens (spherical or non spherical), an arrangement of lenses, a diffractive optical element and the like. The purpose of the collimating procedure is for improving the imaging ability.

In case of a converging lens, a light ray going through a typical converging lens that is normal to the lens and passes through its center, defines the optical axis. The bundle of rays passing through the lens cluster about this axis and may be well imaged by the lens, for example, if the source of the light is located as the focal plane of the lens, the image constituted by the light is projected to infinity.

Other collimating means, *e.g.*, a diffractive optical element, may also provide imaging functionality, although for such means the optical axis is not well defined. The advantage of a converging lens is due to its symmetry about the optical axis, whereas the advantage of a diffractive optical element is due to its compactness.

Representative examples for light source **127** include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs or OLEDs, and the like. Representative examples for image carrier **29** include, without limitation, a miniature slide, a reflective or transparent microfilm and a hologram. The light source can be positioned either in front of the image carrier (to allow reflection of light therefrom) or behind the image carrier (to allow transmission of light therethrough). Optionally and preferably, system **121** comprises a miniature CRT. Miniature CRTs are known in the art and are commercially available, for example, from Kaiser Electronics, a Rockwell Collins business, of San Jose, California.

A digital image generating system typically comprises at least one display and a collimator. The use of certain displays may require, in addition, the use of a light source. In the embodiments in which system **121** is formed of two or more separate units, one unit can comprise the display and light source, and the other unit can comprise the collimator.

Light sources suitable for a digital image generating system include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs (*e.g.*, red, green and blue LEDs) or OLEDs, and the like. Suitable displays include, without limitation, rear-illuminated transmissive or front-illuminated reflective LCD, OLED arrays, Digital Light Processing™ (DLP™) units, miniature plasma display, and the like.. A positive display, such as OLED or miniature plasma display, may not require the use of additional light source for illumination. Transparent miniature LCDs are commercially available, for example, from Kopin Corporation, Taunton, Massachusetts. Reflective LCDs are are commercially available, for example, from Brillian Corporation, Tempe, Arizona. Miniature OLED arrays are commercially available, for example, from eMagin Corporation, Hopewell Junction, New York. DLP™ units are commercially available, for example, from Texas Instruments DLP™ Products, Plano, Texas. The pixel resolution of the digital miniature displays varies from QVGA (320×240 pixels) or smaller, to WQUXGA (3840×2400 pixels).

System **100** is particularly useful for enlarging a field-of-view of devices having relatively small screens. For example, cellular phones and personal digital assistants (PDAs) are known to have rather small on-board displays. PDAs are also known as Pocket PC, such as the trade name iPAQ™ manufactured by Hewlett-Packard Company, Palo Alto, California. The above devices, although capable of storing and downloading a substantial amount of information in a form of single frames or moving images, fail to provide the user with sufficient field-of-view due to their small size displays.

Thus, according to a preferred embodiment of the present invention system **100** comprises a data source **125** which can communicate with system **121** via a data source interface **123**. Any type of communication can be established between interface **123** and data source **125**, including, without limitation, wired communication, wireless communication, optical communication or any combination thereof. Interface **123** is preferably configured to receive a stream of imagery data (*e.g.*, video, graphics, *etc.*) from data source **125** and to input the data into system **121**. Many types or data sources are contemplated. According to a preferred embodiment of the present invention data source **125** is a communication device, such as, but not limited to, a cellular telephone, a personal digital assistant and a portable computer (laptop). Additional examples for data source **125** include, without limitation, television apparatus, portable television device, satellite receiver, video cassette recorder, digital versatile disc (DVD) player, digital moving picture player (*e.g.*, MP4 player), digital camera, video graphic array (VGA) card, and many medical imaging apparatus, *e.g.*, ultrasound imaging apparatus, digital X-ray apparatus (*e.g.*, for computed tomography) and magnetic resonance imaging apparatus.

In addition to the imagery information, data source **125** may generates also audio information. The audio information can be received by interface **123** and provided to the user, using an audio unit **31** (speaker, one or more earphones, *etc.*).

According to various exemplary embodiments of the present invention, data source **125** provides the stream of data in an encoded and/or compressed form. In these embodiments, system **100** further comprises a decoder **33** and/or a decompression unit **35** for decoding and/or decompressing the stream of data to a format which can be recognized by system **121**. Decoder **33** and decompression unit **35** can be supplied as two separate units or an integrated unit as desired.

System **100** preferably comprises a controller **37** for controlling the functionality of system **121** and, optionally and preferably, the information transfer between data source **125** and system **121**. Controller **37** can control any of the display characteristics of system **121**, such as, but not limited to, brightness, hue, contrast, pixel resolution and the like. Additionally, controller **37** can transmit signals to data source **125** for controlling its operation. More specifically, controller **37** can activate, deactivate and select the operation mode of data source **125**. For example, when data source **125** is a television apparatus or being in communication with a broadcasting station, controller **37** can select the displayed channel; when data source **125** is a DVD or MP4 player, controller **37** can select the track from which the stream of data is read; when audio information is transmitted, controller **37** can control the volume of audio unit **31** and/or data source **125**.

System **100** or a portion thereof (*e.g.*, device **10**) can be integrated with a wearable device, such as, but not limited to, a helmet or spectacles, to allow the user to view the image, preferably without having to hold optical relay device **10** by hand.

Device **10** can also be used in combination with a vision correction device **128** (not shown, see Figure 10), for example, one or more corrective lenses for correcting, *e.g.*, short-sightedness (myopia). In this embodiment, the vision correction device is preferably positioned between the eyes and device **20**. According to a preferred embodiment of the present invention system **100** further comprises correction device **128**, integrated with or mounted on device **10**.

Alternatively system **100** or a portion thereof can be adapted to be mounted on an existing wearable device. For example, in one embodiment device **10** is manufactured as a spectacles clip which can be mounted on the user's spectacles, in another embodiment, device **10** is manufactured as a helmet accessory which can be mounted on a helmet's screen.

Reference is now made to Figures 10a-c which illustrate a wearable device **110** in a preferred embodiment in which spectacles are used. According to the presently preferred embodiment of the invention device **110** comprises a spectacles body **112**, having a housing **114**, for holding image generating system **21** (not shown, see Figure 9); a bridge **122** having a pair of nose clips **118**, adapted to engage the user's nose; and rearward extending arms **116** adapted to engage the user's ears. Optical relay device **10** is preferably mounted between housing **114** and bridge **122**, such that when

the user wears device **110**, element **17** is placed in front of first eye **25**, and element **15** is placed in front of second eye **30**. According to a preferred embodiment of the present invention device **110** comprises a one or more earphones **119** which can be supplied as separate units or be integrated with arms **116**.

Interface **123** (not explicitly shown in Figures 10a-c) can be located in housing **114** or any other part of body **112**. In embodiments in which decoder **33** is employed, decoder **33** can be mounted on body **112** or supplied as a separate unit as desired. Communication between data source **25** and interface **123** can be, as stated, wireless, in which case no physical connection is required between wearable device **110** and data source **25**. In embodiments in which the communication is not wireless, suitable communication wires and/or optical fibers **120** are used to connect interface **123** with data source **25** and the other components of system **100**.

The present embodiments can also be provided as add-ons to the data source or any other device capable of transmitting imagery data. Additionally, the present embodiments can also be used as a kit which includes the data source, the image generating system, the binocular device and optionally the wearable device. For example, when the data source is a communication device, the present embodiments can be used as a communication kit.

Additional objects, advantages and novel features of the present invention will become apparent to one ordinarily skilled in the art upon examination of the following examples, which are not intended to be limiting. Additionally, each of the various embodiments and aspects of the present invention as delineated hereinabove and as claimed in the claims section below finds experimental support in the following examples.

EXAMPLES

Reference is now made to the following examples, which together with the above descriptions illustrate the invention in a non limiting fashion.

EXAMPLE 1

Diffraction of Red Light

Following is a non-limiting example in which planar dimension calculations are performed in accordance with the teachings of the preferred embodiments of the invention for the diffraction of red light.

The present calculations are for 509 nm period gratings formed in a light transmissive substrate having index of refraction of 1.522 and thickness of 2 mm. As a representative example for red light, a wavelength of 615 nm was assumed.

With the above values of the grating period, index of refraction and wavelength a longitudinal field-of-view Ω_y of [−12.0°, +12.0°] and a transverse field-of-view Ω_x of [−9.0°, +9.0°] can be achieved. The overall (diagonal) field-of-view Ω is calculated using Equation 5 to obtain Ω = [−15°, +15°].

For $\Delta z = 25$ mm, the minimal dimensions of the output optical element(s) are (see Equation 6) $L_{O,\ min} = 10.6$ mm and $W_{O,min} = 7.9$ mm. For $L_{EB} = 4$ mm, $W_{EB} = 1$ mm and $O_p = 3$ mm, the dimensions of the output optical element(s) are (see Equation 7) $L_O = 17.6$ mm and $W_O = 11.9$ mm.

Using the thickness of the substrate and the above values of Ω_y one obtains a hop-length of $h = 3.5$ mm which is then used to set the length L_I of the input element to be from about 3.5 mm to about 10.5 mm.

The above values of Ω_x and Ω_y correspond to an outermost propagation angle (as projected on the *x-y* plane) of ±8.8°. Thus, in accordance with preferred embodiments of the present invention, the value of the angular parameter γ is 8.8°.

For $\Delta y = 17.7$ mm, and $L_I = 10$ mm, the width W_I of the input optical element is (see Equation 8) is $W_I = 22.8$ mm.

EXAMPLE 2

Diffraction of Blue Light

Following is a non-limiting example in which planar dimension calculations are performed in accordance with the teachings of the preferred embodiments of the invention for the diffraction of blue light.

The present calculations are for 389 nm period gratings formed in a light transmissive substrate having index of refraction of 1.529 and thickness of 1.8 mm. As a representative example for blue light, a wavelength of 465 nm was assumed.

With the above values of the grating period, index of refraction and wavelength a longitudinal field-of-view Ω_y of [−11°, +11°] and a transverse field-of-view Ω_x of [−8.3°, +8.3°] can be achieved. The overall (diagonal) field-of-view Ω is calculated using Equation 5 to obtain Ω = [−13.7°, +13.7°].

For $\Delta z = 20$ mm, the minimal dimensions of the output optical element(s) are $L_{O,\min} = 7.8$ mm and $W_{O,\min} = 5.8$ mm. For $L_{EB} = 5$ mm, $W_{EB} = 2$ mm and $O_p = 3$ mm the dimensions of the output optical element(s) are $L_O = 15.8$ mm and $W_O = 10.8$ mm.

Using the thickness of the substrate and the above values of Ω_y one obtains a hop-length of $h = 3.1$ mm, which is then used to set the length L_I of the input element to be from about 3 mm to about 10 mm.

The above values of Ω_x and Ω_y correspond to an outermost propagation angle (as projected on the x-y plane) of ±8°, hence $\gamma = 8°$, in accordance with preferred embodiments of the present invention.

For $\Delta y = 16.6$ mm and $L_I = 9$ mm, the width W_I is 19.9 mm.

EXAMPLE 3

Non-uniform Duty cycle

Figures 11a-d show numerical calculations of the diffraction efficiency of a grating as a function of the duty cycle, for impinging angles ϕ_{iy} of 50° (Figures 11a-b) and 55° (Figures 11c-d), and modulation depths δ of 150 nm (Figures 11a and 11c) and 300 nm (Figures 11b and 11d). The different curves in Figures 11a-d correspond to wavelengths of 480 nm (solid line), 540 nm (dashed line) and 600 nm (dot-dash line). The calculations were based on the Maxwell equations, for 455 nm period grating formed in a light transmissive substrate having index of refraction of 1.53.

EXAMPLE 4

Non-uniform Modulation Depth

Figures 12a-b show numerical calculations of the diffraction efficiency of a grating as a function of the modulation depth δ, for impinging angles ϕ_{iy} of 50° (Figure 12a) and 55° (Figure 12b), and duty cycle of 0.5. The different curves in Figures 12a-b correspond to wavelengths of 480 nm (solid line), 540 nm (dashed line) and 600 nm (dot-dash line). The calculations were based on the Maxwell equations, for 455 nm period grating formed in a light transmissive substrate having index of refraction of 1.53.

As shown in Figures 12-a-b, the diffraction efficiency increases with increasing δ up to modulation depth of about 200-250 nm. Above about 250 nm, the diffraction efficiency decreases with increasing δ up to modulation depth of about 400-500 nm.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination.

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims. All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.

WHAT IS CLAIMED IS:

1. An optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view, the device comprising:

a light-transmissive substrate engaging a plane spanned by a longitudinal direction and a transverse direction;

an input optical element designed and constructed for redirecting the light such that the light propagates within said light-transmissive substrate via total internal reflection; and

an output optical element, laterally displaced from said input optical element, and being designed and constructed for redirecting the light out of said light-transmissive substrate;

said output optical element being characterized by planar dimensions defined by a length along said longitudinal direction and a width along said transverse direction, wherein said length and said width are selected such that at least a portion of at least one outermost light ray within the field-of-view is directed to a two-dimensional region being at a predetermined distance from said light transmissive substrate.

2. The device of claim 1, wherein said predetermined distance is from about 15 millimeters to about 35 millimeters.

3. The device of claim 2, wherein a width of said two-dimensional region is from about 4 millimeters to about 9 millimeters.

4. The device of claim 2, wherein a length of said two-dimensional region is from about 5 millimeters to about 13 millimeters.

5. The device of claim 1, wherein said width of said output optical element is smaller than a width of said input optical element.

6. The device of claim 1, wherein at least one of said input optical element and said output optical element is a diffractive optical element.

7. An optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view, the device comprising:

a light-transmissive substrate engaging a plane spanned by a longitudinal direction and a transverse direction;

an input optical element designed and constructed for redirecting the light such that the light propagates within said light-transmissive substrate via total internal reflection;

a first output optical element, laterally displaced from said input optical element, and being designed and constructed for redirecting light corresponding to a first partial field-of-view out of said light-transmissive substrate; and

a second output optical element, laterally displaced from said input optical element and said first output optical element, and being designed and constructed for redirecting light corresponding to a second partial field-of-view out of said light-transmissive substrate;

each of said first and said second output optical elements being characterized by planar dimensions defined by a length along said longitudinal direction and a width along said transverse direction, wherein a length and a width of said first output optical element are selected such that at least a portion of at least one outermost light ray within said first partial field-of-view is directed to a first two-dimensional region, and a length and a width of said second output optical element are selected such that at least a portion of at least one outermost light ray within said second partial field-of-view is directed to a second two-dimensional region, said first and said second two-dimensional regions being at a predetermined distance from said light transmissive substrate.

8. A system for providing an image to a user, comprising the optical relay device of claim 7, and an image generating system for providing said optical relay device with collimated light constituting said image.

9. The device or system of claim 7 or 8, wherein a lateral separation between the centers of said first two-dimensional region and said second two-dimensional region is at least 40 millimeters.

10. The device or system of claim 9, wherein said lateral separation is less than 80 millimeters.

11. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 40 millimeters and smaller than 80 millimeters.

12. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 50 millimeters and smaller than 65 millimeters.

13. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 53 millimeters and smaller than 73 millimeters.

14. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 53 millimeters and smaller than 63 millimeters.

15. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 58 millimeters and smaller than 68 millimeters.

16. The device or system of claim 9, wherein said planar dimensions are selected such that said portions of said outermost light rays are respectively directed to said first and said second two-dimensional regions, for any lateral separation which is larger than 63 millimeters and smaller than 73 millimeters.

17. The device or system of claim 7 or 8, wherein each of said width of said first output optical element and said width of said second output optical element is smaller than a width of said input optical element.

18. An optical relay device for transmitting an image by diffraction to a first eye and a second eye characterized by an interpupillary distance, the device comprising a light transmissive substrate and a plurality of diffractive optical elements located at fixed locations on said light transmissive substrate, the optical relay device being characterized by a field-of-view of at least 16 degrees, and being capable of providing the image for any interpupillary distance from about 40 millimeters to about 80 millimeters.

19. A system for providing an image to a user, comprising the optical relay device of claim 18, and an image generating system for providing said optical relay device with collimated light constituting said image.

20. The device or system of claim 18 or 19, wherein said plurality of diffractive optical elements comprises an input diffractive optical element, a first output diffractive optical element and a second output diffractive optical element, said input diffractive optical element being designed and constructed for diffracting light constituting the image to propagate within said light-transmissive substrate via total internal reflection, and said output diffractive optical elements being designed and constructed for diffracting at least a portion of said light out of said light transmissive substrate.

21. The device or system of claim 20, wherein said first output diffractive optical element is designed and constructed for diffracting light corresponding to a first partial field-of-view of the image out of said light-transmissive substrate, and said second output diffractive optical element is designed and constructed for diffracting light corresponding to a second partial field-of-view of the image out of said light-transmissive substrate, such that the combination of said first and said second partial field-of-views substantially reconstructs said field-of-view.

22. The device or system of claim 20, wherein said first and said second diffractive optical elements are characterized by planar dimensions selected such that at least a portion of at least one outermost light ray within said first partial field-of-view is directed to a first two-dimensional region containing the first eye, and at least a portion of at least one outermost light ray within said second partial field-of-view is directed to a second two-dimensional region containing the second eye, said first and said second two-dimensional regions being at a predetermined distance from said light transmissive substrate.

23. The device or system of claim 7 or 8, wherein said predetermined distance is from about 15 millimeters to about 35 millimeters.

24. The device or system of claim 23, wherein a width of each of said first two-dimensional region and said second two-dimensional region is from about 4 millimeters to about 9 millimeters.

25. The device or system of claim 23, wherein a length of each of said first two-dimensional region and said second two-dimensional region is from about 5 millimeters to about 13 millimeters.

26. The device or system of claim 1, 7, 8 or 20, wherein a length of said input optical element equals from about X to about $3X$ where X is a minimal unit hop-length characterizing propagation of an outermost light ray within said light transmissive substrate via total internal reflection.

27. The device or system of claim 1, 7, 8 or 20, wherein the light is characterized by a spectrum inclusively defined between a shortest wavelength and a longest wavelength.

28. The device or system of claim 27, wherein a length of said input optical element equals from about X to about $3X$ where X is a unit hop-length characterizing propagation of a light ray having said shortest wavelength within said light transmissive substrate via total internal reflection.

29. The device or system of claim 7 or 8, wherein at least one of said input optical element, said first output optical element and said second output optical element is a diffractive optical element.

30. The device or system of claim 6, 14, 15 or 25, wherein at least one diffractive optical element comprises a grating described by non-uniform diffraction efficiency function.

31. The device or system of claim 30, wherein said grating has a periodic linear structure in at least one direction, said periodic linear structure being characterized by non-uniform duty cycle.

32. The device or system of claim 30, wherein said grating has a periodic linear structure in at least one direction, said periodic linear structure being characterized by non-uniform modulation depth.

33. The device or system of claim 30, wherein said grating has a periodic linear structure in at least one direction, said periodic linear structure being characterized by non-uniform duty cycle and non-uniform modulation depth.

34. The device or system of claim 31 or 32, wherein said non-uniform diffraction efficiency function is monotonic across said at least one direction.

35. The device or system of claim 30, wherein said non-uniform diffraction efficiency function is selected such that when a light ray impinges on said grating a plurality of times, a predetermined and substantially constant fraction of the energy of said light is diffracted at each impingement.

36. The device or system of claim 30, wherein said grating is formed in said light transmissive substrate.

37. The device or system of claim 30, wherein said grating is attached to said light transmissive substrate.

38. An optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view, the device comprising:

a light-transmissive substrate engaging a plane spanned by a longitudinal direction and a transverse direction;

an input optical element designed and constructed for redirecting the light such that the light propagates within the light-transmissive substrate via total internal reflection; and

at least one output optical element, laterally displaced from said input optical element, and being designed and constructed for redirecting the light out of said light-transmissive substrate;

each of said input optical element and said at least one output optical element being characterized by planar dimensions defined by a length along said longitudinal direction and a width along said transverse direction, wherein a width of said at least one output optical element is smaller than a width of said input optical element.

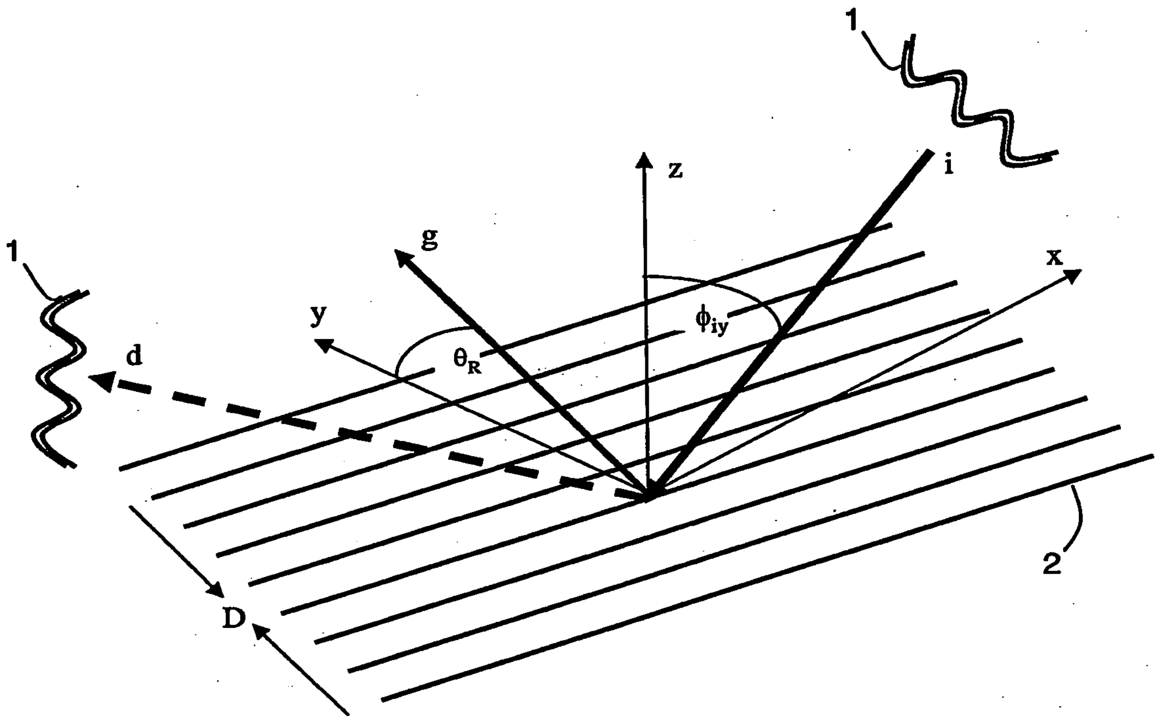
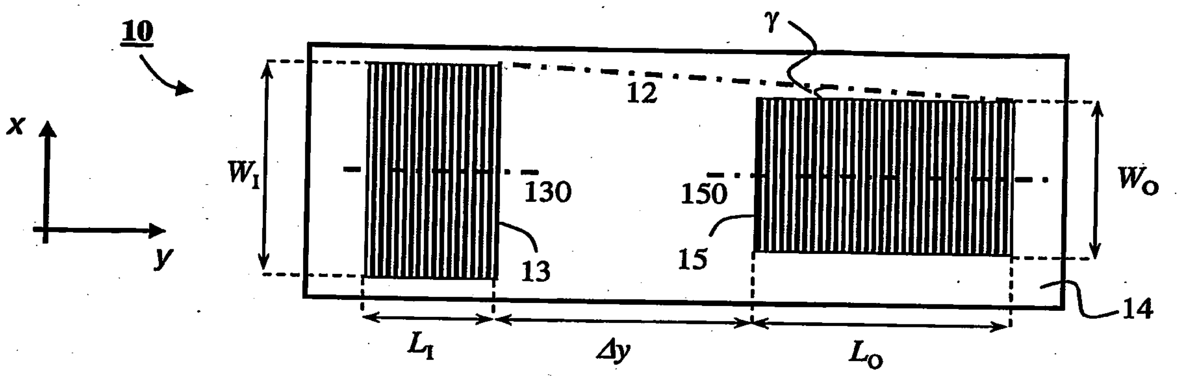


Fig. 1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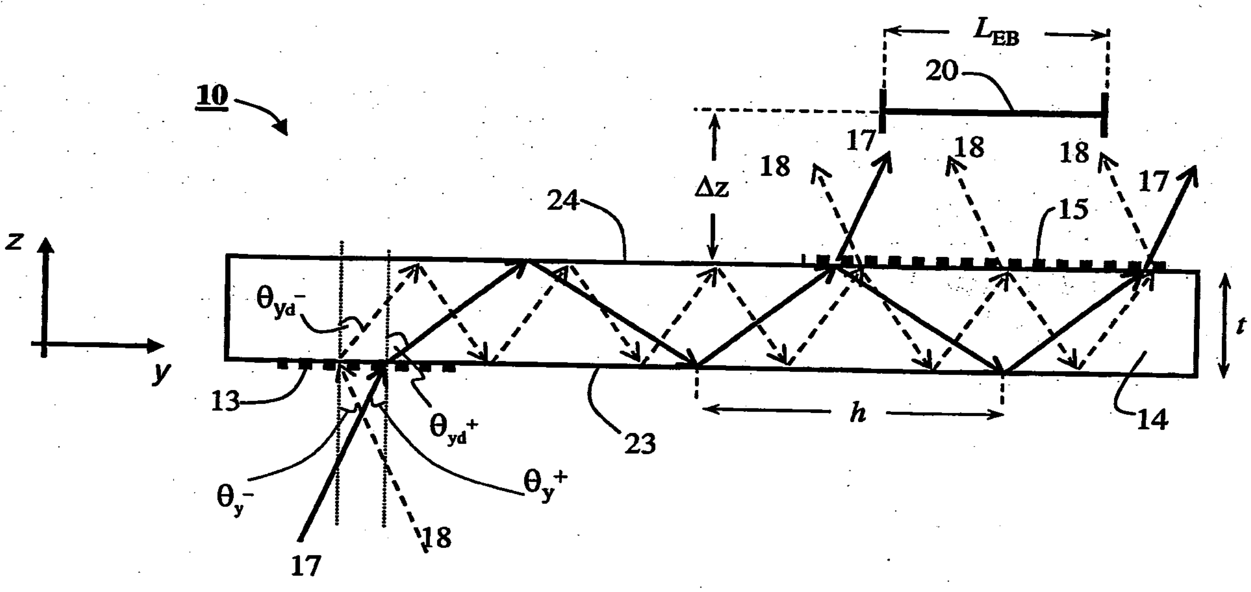
γ
12
x
y
W_I
130
150
W_O
13
15
14
L_I
Δy
L_O

Fig. 2a


L_{EB}
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10
17
18
18
18
17
Δz
24
15
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18
17

Fig. 2b

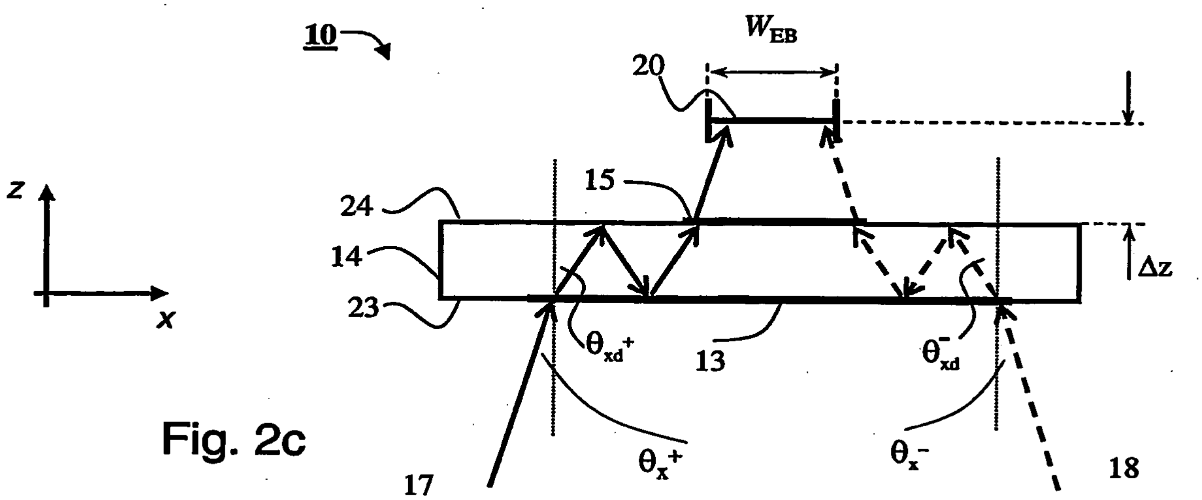


Fig. 2c

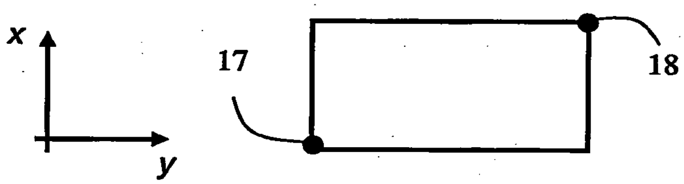


Fig. 2d

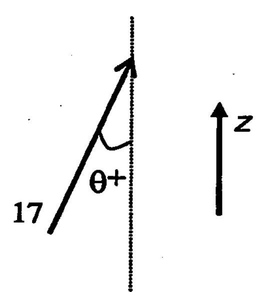


Fig. 2e

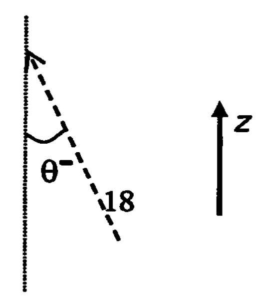
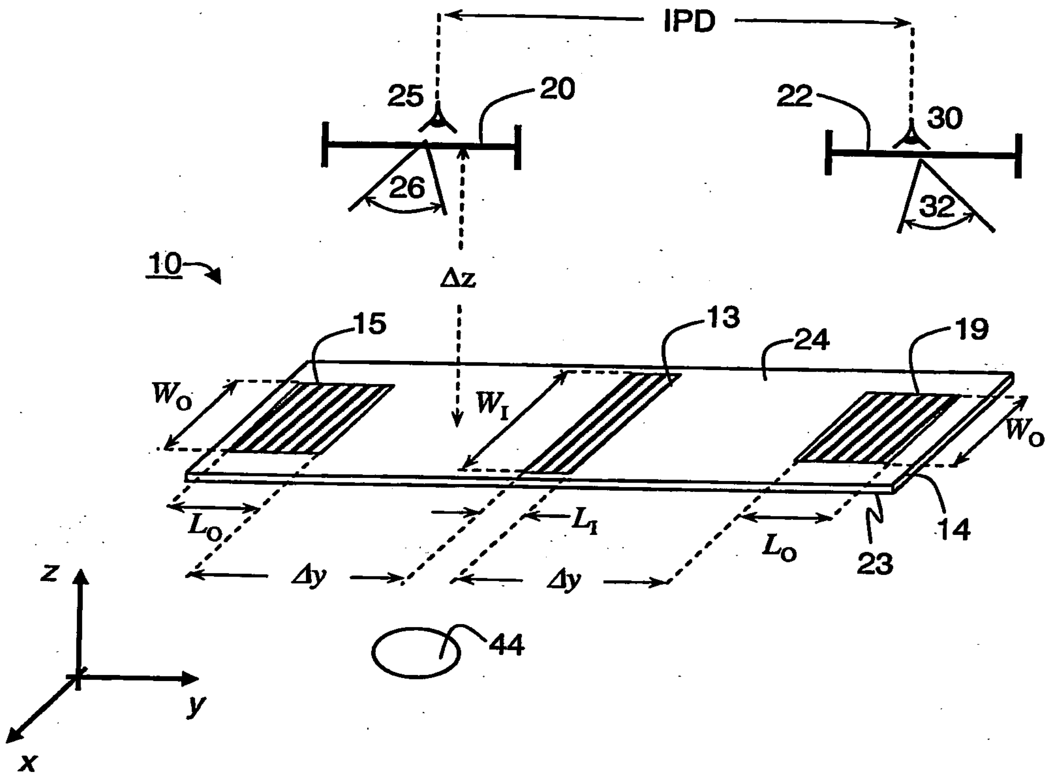


Fig. 2f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30
26
32
10
Δz
15
13
24
19
W_O
W_I
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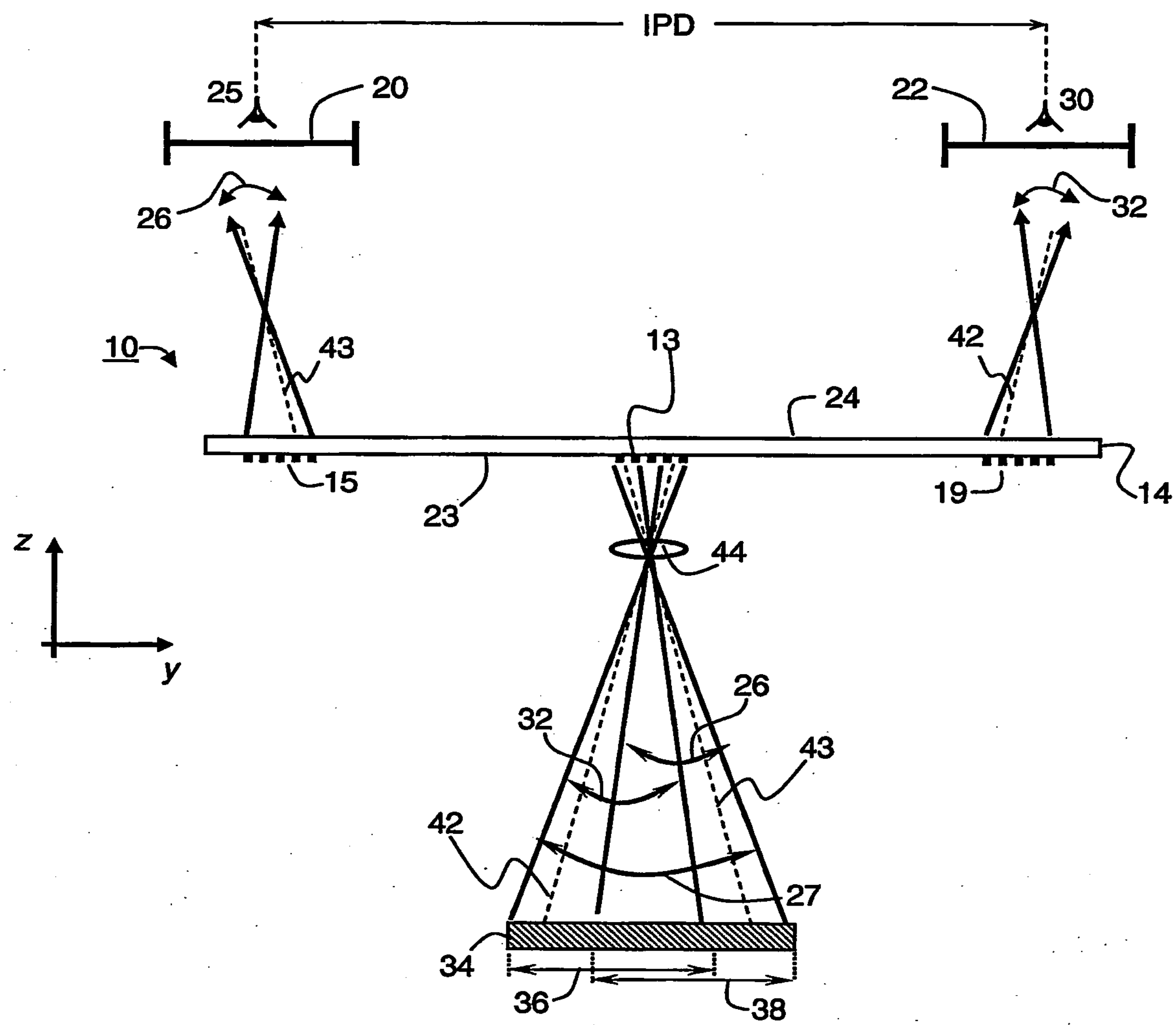
L_O
14
23
Δy
Δy
z
y
x
44

Fig. 3a


IPD
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20
22
30
26
32
10
43
13
42
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23
19
14
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y
44
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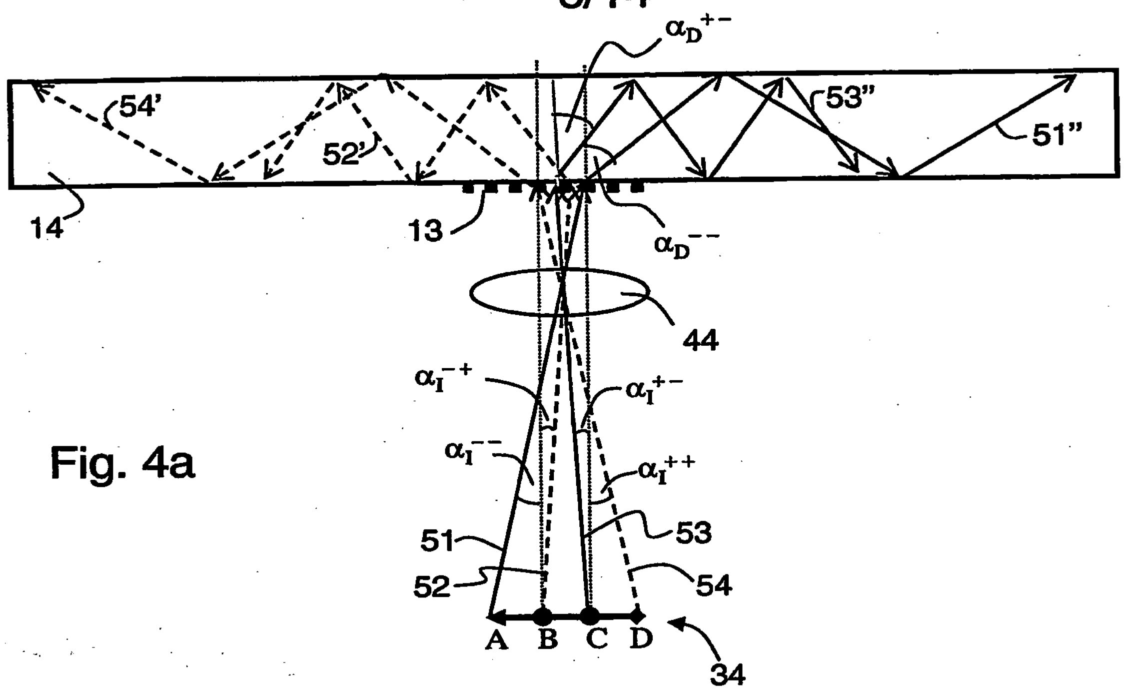
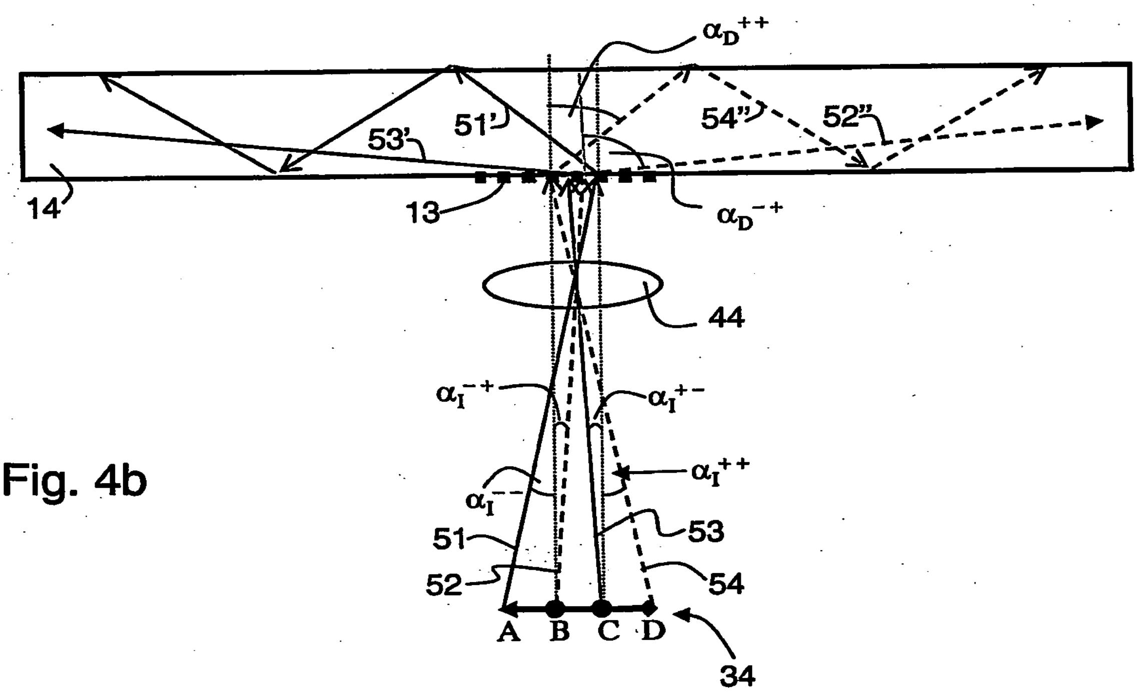
34
36
38

Fig. 3b



αD+-
54'
52'
53"
51"
14
13
αD--
44
αI-+
αI+-
αI--
αI++
51
53
52
54
A B C D
34

Fig. 4a



αD++
51'
53'
54"
52"
14
13
αD-+
44
αI-+
αI+-
αI++
αI--
51
53
52
54
A B C D
34

Fig. 4b

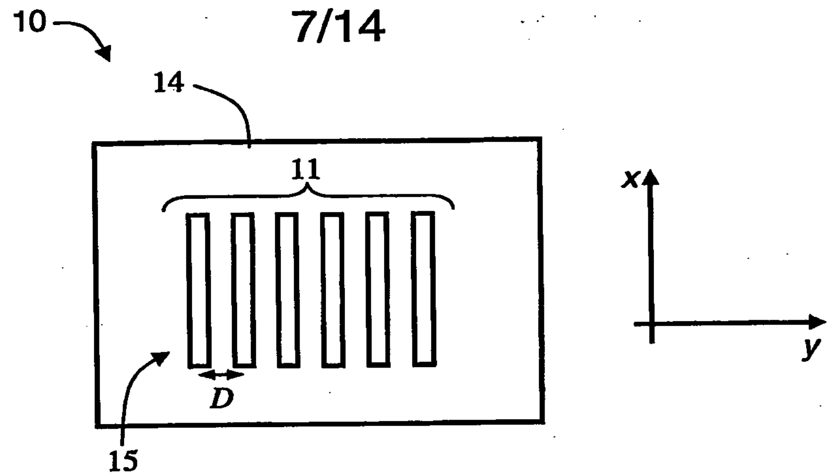


Fig. 5a

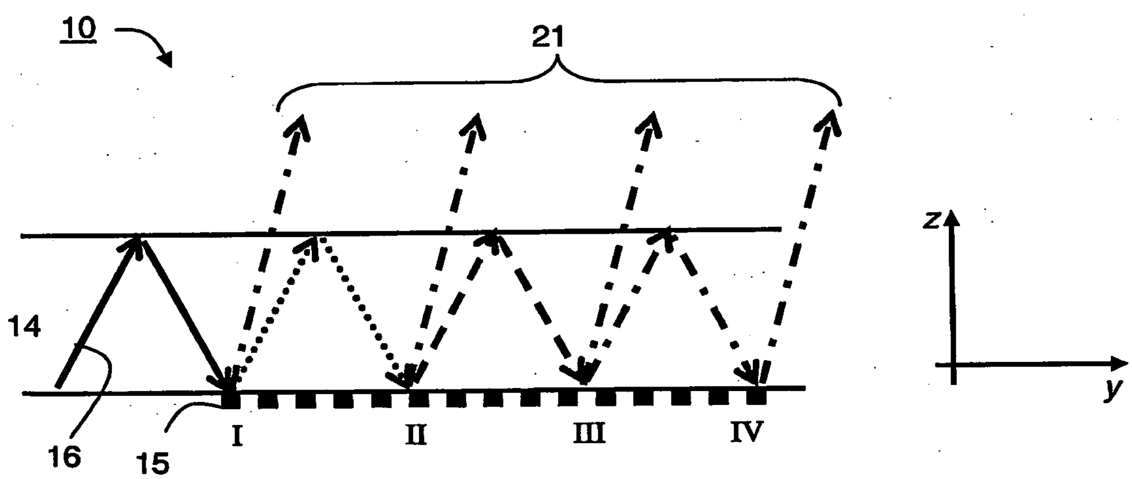


Fig. 5b

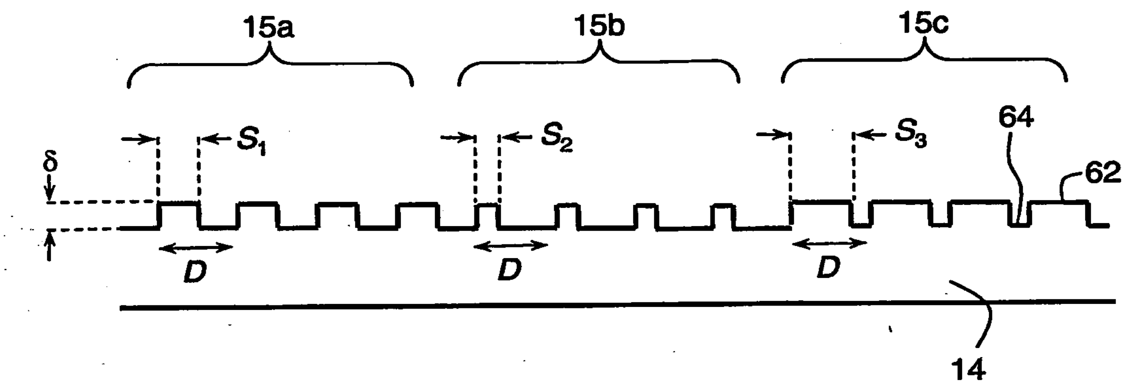

15a
15b
15c
S_1
S_2
S_3
64
62
δ
D
D
D
14

Fig. 6

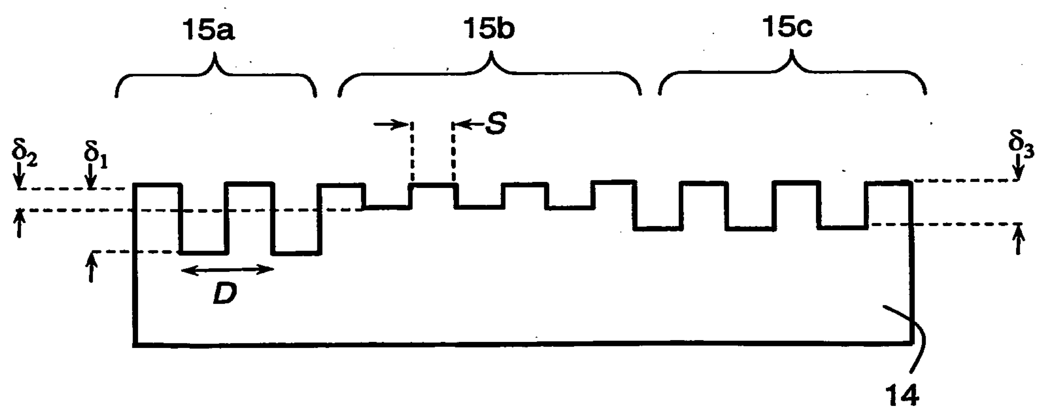

15a
15b
15c
S
δ_2
δ_1
δ_3
D
14

Fig. 7

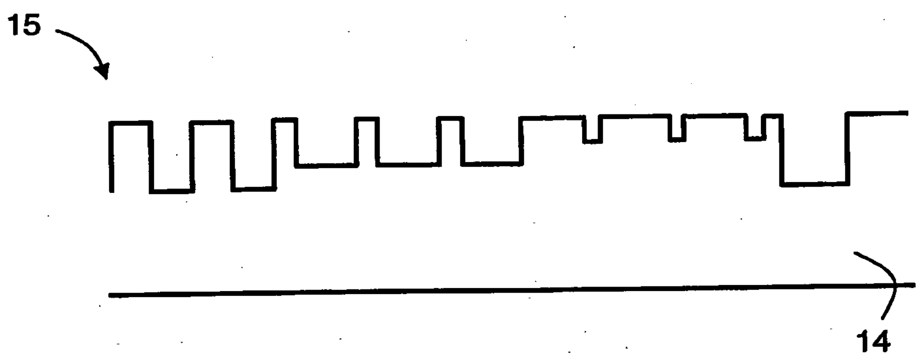


Fig. 8

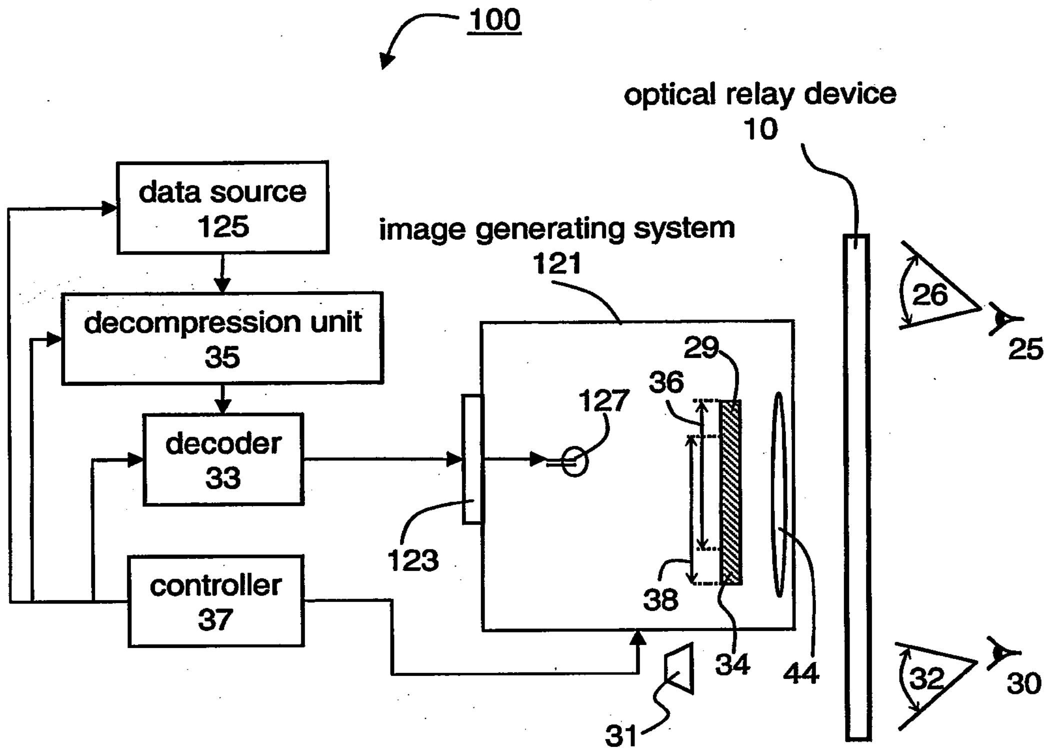

100
optical relay device
10
data source
125
image generating system
121
decompression unit
35
decoder
33
controller
37
127
123
29
36
38
34
44
31
26
25
32
30

Fig. 9

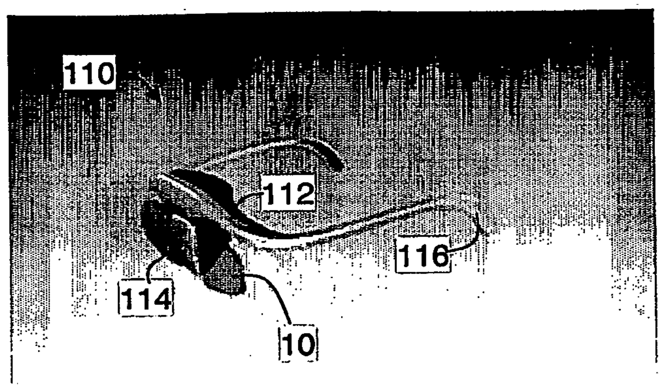


Fig. 10a

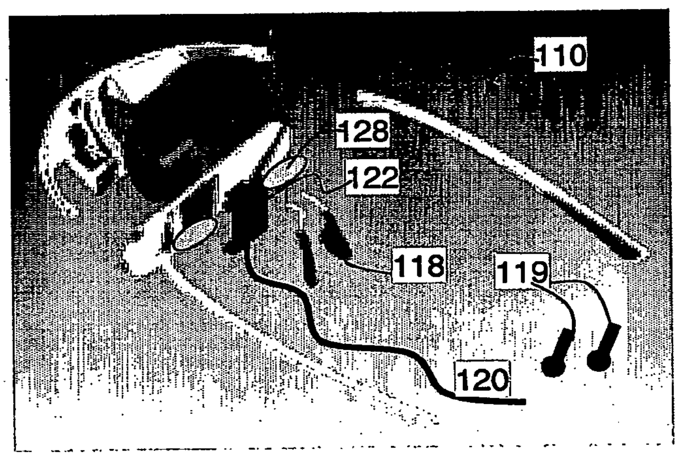


Fig. 10b

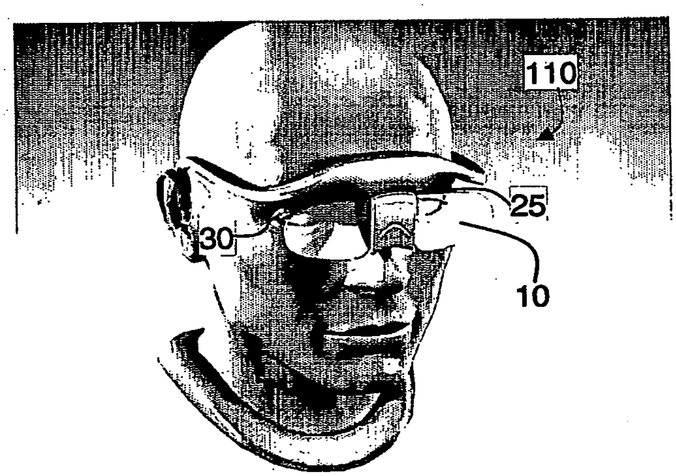


Fig. 10c

Fig. 11a

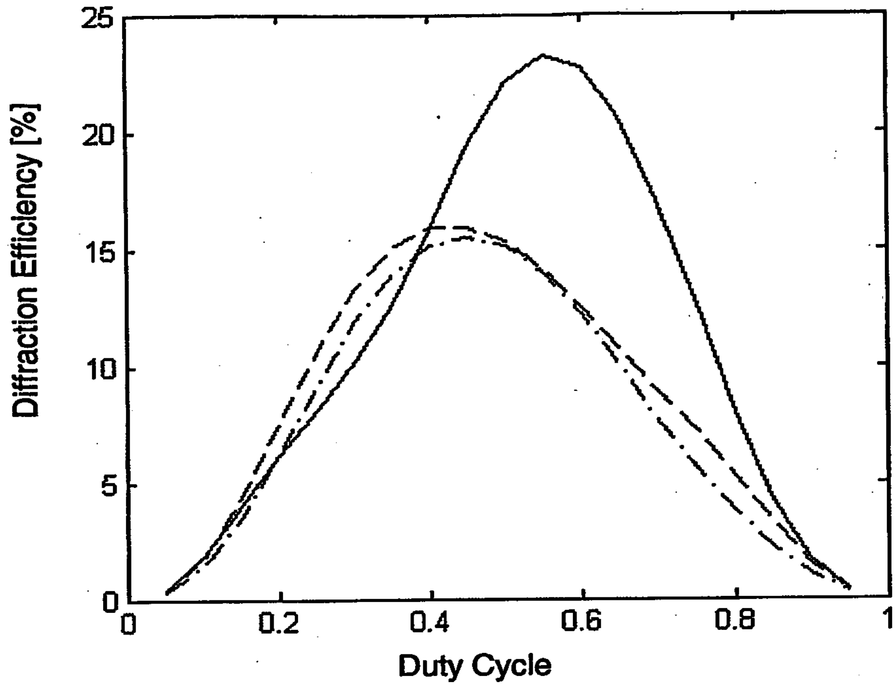


Fig. 11b

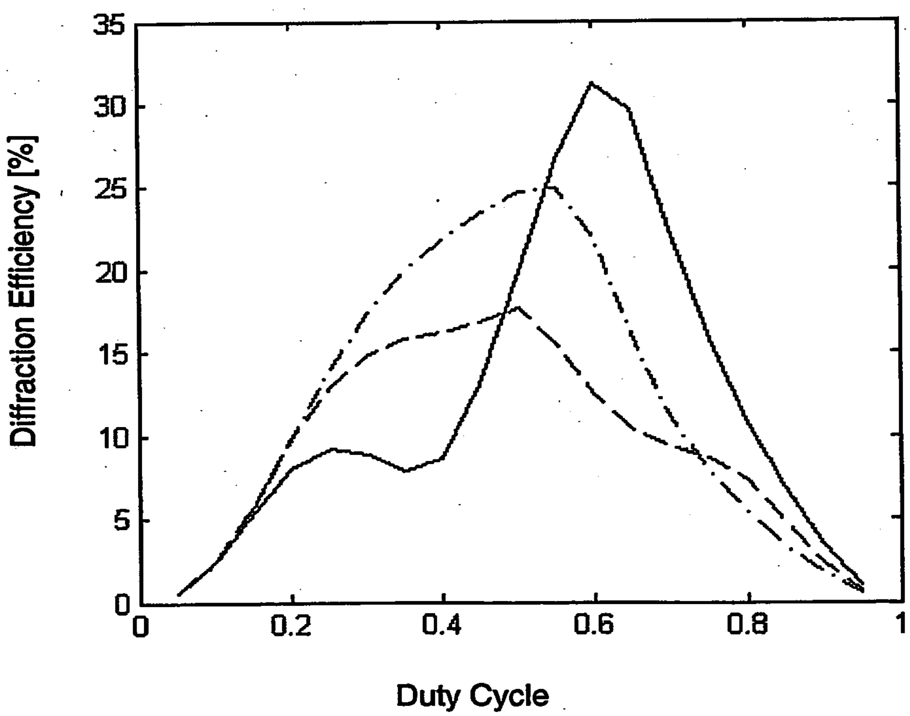


Fig. 11c

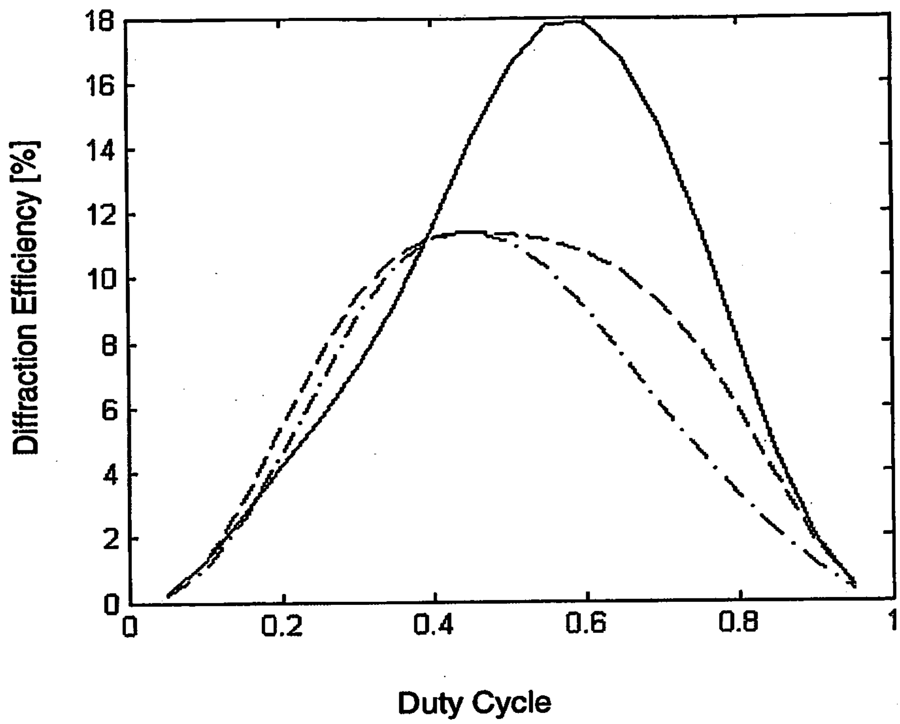


Fig. 11d

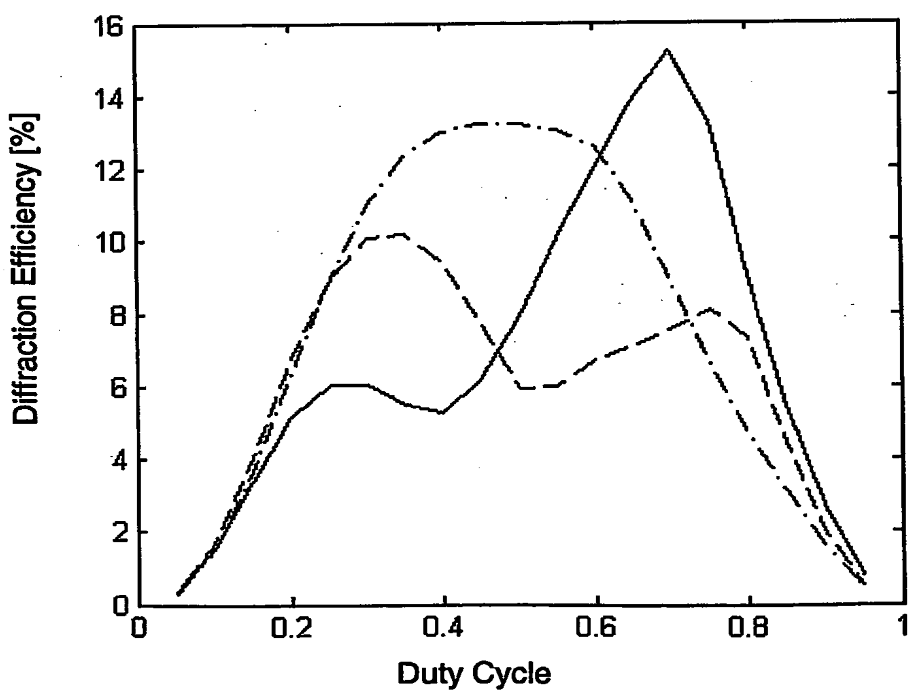


Fig. 12a

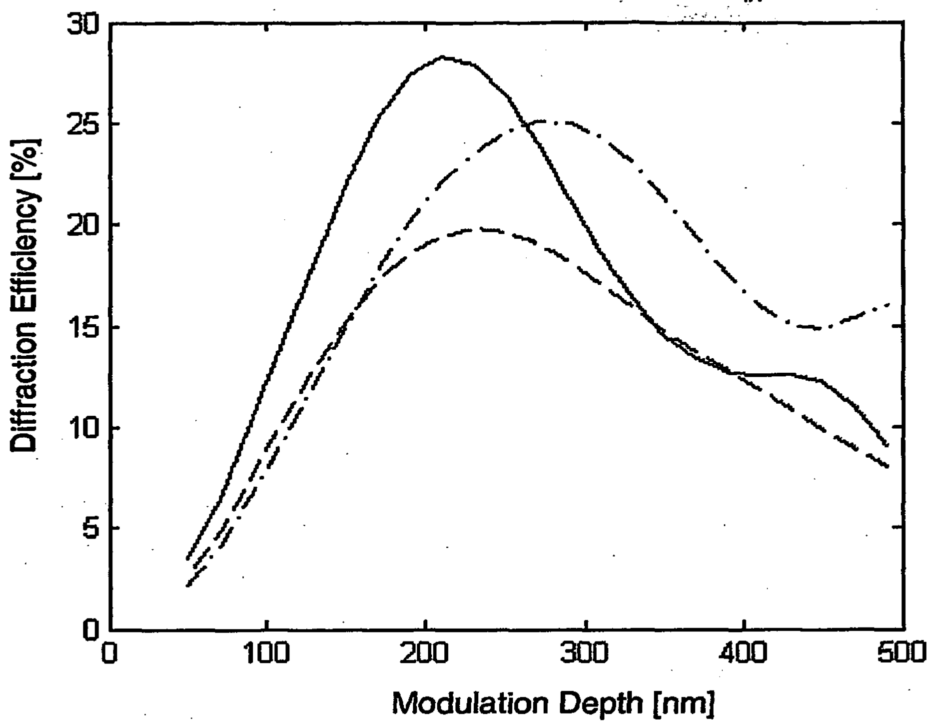
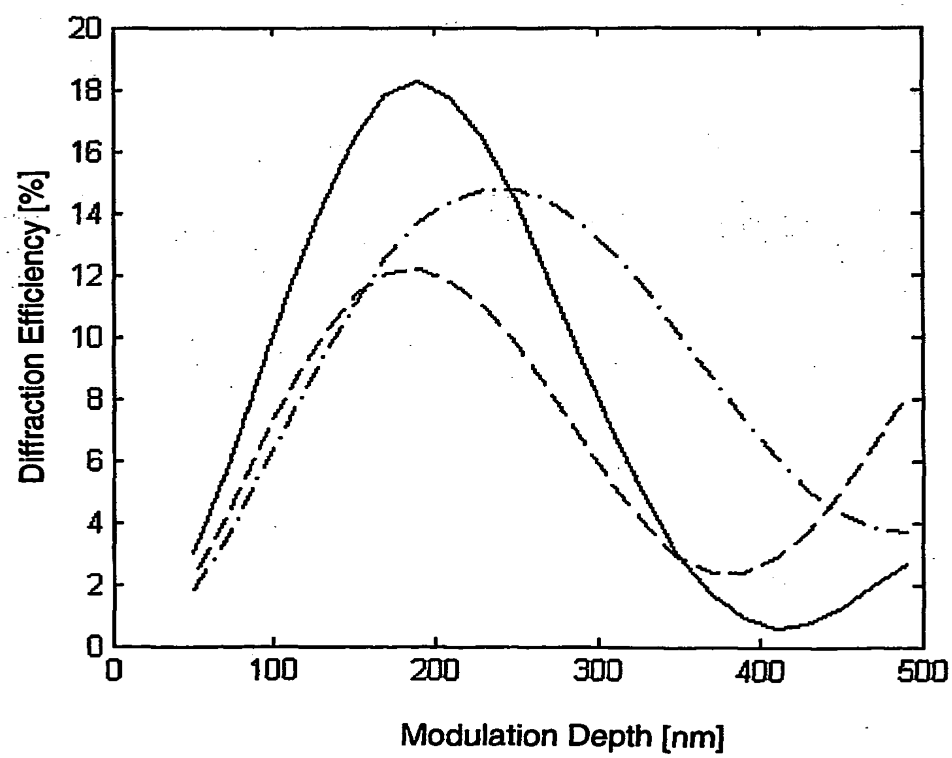


Fig. 12b



(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 March 2007 (22.03.2007)

PCT

(10) International Publication Number
WO 2007/031991 A3

(51) International Patent Classification:
G02B 27/01 (2006.01) *G02B 6/00* (2006.01)
G02B 5/32 (2006.01) *G02B 5/18* (2006.01)

(21) International Application Number:
PCT/IL2006/001050

(22) International Filing Date:
7 September 2006 (07.09.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/716,533	14 September 2005 (14.09.2005)	US
60/732,661	3 November 2005 (03.11.2005)	US
60/801,410	19 May 2006 (19.05.2006)	US
11/505,866	18 August 2006 (18.08.2006)	US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 11/505,866 (CIP)
Filed on 18 August 2006 (18.08.2006)

(71) Applicant *(for all designated States except US)*: **MIRAGE INNOVATIONS LTD.** [IL/IL]; 21 Yagea Kapayim Street, Kiryat Aryeh, P.O Box 10013, 49001 Petach-Tikva (IL).

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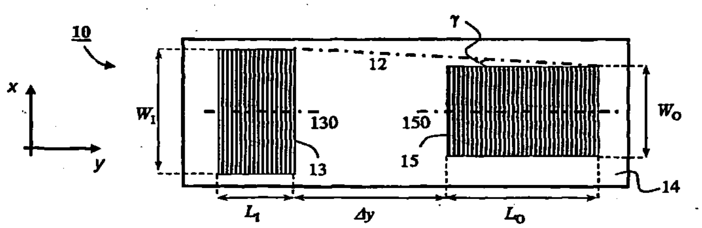
(74) Agents: **G.E. EHRLICH (1995) LTD.** et al.; 11 Menachem Begin Street, 52 521 Ramat Gan (IL).

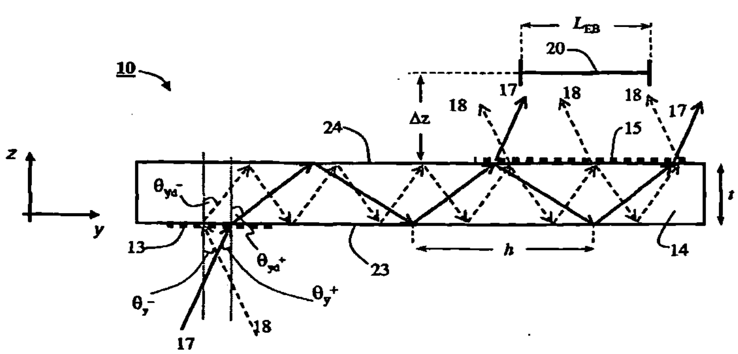
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU,

[Continued on next page]

(54) Title: DIFFRACTIVE OPTICAL DEVICE AND SYSTEM



a



b

(57) Abstract: An optical relay device for transmitting light striking the optical relay device at a plurality of angles within a field-of-view is provided. The device comprises a light-transmissive substrate, an input optical element and an output optical element. The input element diffracts the light to propagate within the light-transmissive substrate via total internal reflection, and the output element diffracts the light out of the substrate. The output element is characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within the field-of-view is directed to a two-dimensional region being at a predetermined distance from the substrate.

WO 2007/031991 A3

SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US (patent), UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(88) Date of publication of the international search report:
7 June 2007

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2006/001050

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/01 G02B5/32 G02B6/00 G02B5/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2002/122015 A1 (SONG YOUNG-RAN [KR] ET AL) 5 September 2002 (2002-09-05) paragraphs [0042] - [0046]; figures 5,6	1-29,38
X	JP 2000 056259 A (FUJI XEROX CO LTD) 25 February 2000 (2000-02-25) abstract; figure 1	1
X	EP 1 536 268 A1 (NIPPON KOGAKU KK [JP]) 1 June 2005 (2005-06-01) paragraphs [0045] - [0059]; figure 1	1
X	WO 2004/109349 A2 (ELOP ELECTROOPTICS IND LTD [IL]; WEISS VICTOR [IL]; GURWICH IOSEPH [IL) 16 December 2004 (2004-12-16) page 27, line 27 - page 28, line 5; figure 1b	30-37

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 February 2007	15/03/2007

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hambach, Dirk

INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2006/001050

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99/52002 A (ELOP ELECTROOPTICS IND LTD [IL]; YEDA RES & DEV [IL]; AMITAI YAAKOV [I) 14 October 1999 (1999-10-14) page 5 - page 6	1,6,30, 35-37
A	JINWON SUNG ET AL: "Analog micro-optics fabrication by use of a binary phase grating mask" MICROMACHINING TECHNOLOGY FOR MICRO-OPTICS AND NANO-OPTICS II 27-29 JAN. 2004 SAN JOSE, CA, USA, vol. 5347, no. 1, 2004, pages 62-70, XP002422582 Proceedings of the SPIE - The International Society for Optical Engineering SPIE-Int. Soc. Opt. Eng USA ISSN: 0277-786X	31,33

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2006/001050

Box II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-29, 38

   Optical relay for different interpupillary distance

   ---

2. claims: 30-37

   Grating with non-uniform diffraction efficiency

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IL2006/001050

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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JP 2000056259 A	25-02-2000	NONE	
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